PROGRESS REPORT NO. 9

DIESEL ENGINE IGNITION AND COMBUSTION

Effect of Type of Fuel, Engine Speed, and Coolant Temperature on Ignition Delay and Other Combustion Phenomena

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PART I

SUMMARY

I. BACKGROUND

A program of activity to study the combustion process in supercharged diesel engines has been developed at The University of Michigan. This program is primarily concerned with the ignition delay and the effect of the several parameters on it. A special concern is given to the effect of the pressure and temperature of the cylinder air charge and engine speed on ignition delay. The program also includes the study of the effect of these variables on the other combustion phenomena such as smoke, rate of pressure rise, and maximum pressure reached in the cylinder.

The different types of delay have been studied in detail and an emphasis is made on the pressure rise delay and illumination delay. The instruments needed for the measurement of these two delay periods have been developed and a continuous effort is being made to improve their accuracy.

This research is being made on two experimental diesel engines. One is the ATAC high output open combustion chamber engine, and the other is a Lister-Blackstone swirl combustion chamber engine. Three fuels have been used in these tests.

II. OBJECTIVES

A. To study how gas pressure at the time of injection affects ignition delay and combustion. The effects are to be studied at pressures ranging from approximately 300 to 1000 psia.

B. To study how gas temperature at the time of injection affects ignition delay. The temperature ranges from approximately 900°F to 1500°F.

C. To study various combinations of pressures and temperatures to determine whether density is an independent variable affecting ignition delay.

D. To conduct all these studies with three funels: CITE refree grade (Mil-F-45121) fuel, diesel no. 2 fuel, and Mil-G-3056 refree grade gasoline.

E. To study the effect of engine speed on the ignition delay and the other combustion phenomena. The engine speed covered a range from 1000 rpm to 3000 rpm.

F. To study the effect of the coolant temperature on the combustion process and the wall temperatures. Coolant temperatures range from 150°F to 300°F.

G. To study the effect of anti-smoke additives on the combustion process and the smoke. The anti-smoke additive is Lubrizol barium compound.

III. CUMULATIVE PROGRESS

A. LISTER-BLACKSTONE ENGINE

Cumulative progress has been made in the following areas:

A. Review and analysis of previous work
B. Theoretical analysis
C. Experimental work on Lister-Blackstone engine
D. Comparison between the present work done on the Lister engine and previous work in bombs and engines

B. ATAC-1 OPEN COMBUSTION CHAMBER ENGINE

The cumulative progress made on ATAC-1 engine can be devided into three major areas:

1. Engine instrumentation
2. Experimental work
3. Theoretical work

1. Engine Instrumentation

The engine has been instrumented and all the instruments calibrated to measure the following:

a. Power output and engine speed
b. Gas pressure during the cycle
c. Illumination due to combustion
d. Wall surface temperature during the cycle
e. Wall temperature in the fire deck near the inlet and exhaust valves
f. Fuel pressure before the injector
g. Injector needle lift
h. Air flow rate into the engine and its temperature and pressure before the inlet valve
i. Fuel flow rate
j. Intensity of smoke in the exhaust gases, their temperature and pressure

2. Experimental Work on ATAC

Experiments were made on the ATAC engine to study the effect of temperature on ignition delay and combustion characteristics of the following fuels:

a. CITE refree grade (Mil-F-45121) fuel
b. Diesel no. 2 fuel
c. Mil-G-3056 refree grade gasoline fuel

The experimental results of this part were given in Progress Report No. 8, under A2A, A2B, A2C, and A2D series.

3. Theoretical Analysis

A thermodynamic analysis was made to study the different types of energy and processes taking place during the ignition delay, and to compare between the different definitions used in the literature for the ignition delay. This study will be published in an SAE paper which will be presented in the International Meeting in Detroit, on January 17, 1969.

IV. PROGRESS DURING THIS PERIOD

During this period the experimental and analytical work on the ATAC engine has been completed, as follows:

a. A comparison between the combustion phenomena and the rate of heat release for the following fuels, under naturally aspirated conditions. The series of tests conducted for this comparison is referred to as series AI.

   1. CITE refree grade (Mil-F-45121) fuel
   2. Diesel no. 2 fuel, and
   3. Mil-G-3056 refree grade gasoline fuel

   The experimental work demonstrated that it was difficult to burn gasoline in the ATAC engine with its present compression ratio of 16.7:1, under naturally aspirated conditions. The heat release computations were therefore only made for CITE and diesel no. 2 fuels. The several computer programs made for these elaborate computations proved to be very successful, and can be used in future heat release computations under any set of running conditions.

b. Effect of engine speed on the ignition delay and other combustion phenomena. Engine speeds covered a range from 1000 rpm to 3000 rpm.

c. Effect of coolant temperature on the combustion process of CITE fuel. The coolant used for these tests was ethylene glycol at temperatures up to 305°F.

V. CONCLUSIONS

The conclusions are stated under the following headings:

A. Effect of type of fuel on I.D. and heat release rate
B. Effect of engine speed on I.D. and other combustion phenomena
C. Effect of coolant temperature on the different combustion phenomena

A. EFFECT OF TYPE OF FUEL ON I.D. AND HEAT RELEASE RATE

The results of the heat release computations, for the diesel no. 2 and CITE fuels, showed that the following processes occur during the ignition delay before the pressure rise due to combustion is detected:

1. A negative heat release at the beginning of the ignition delay, due to fuel evaporation and the endothermic reactions that take place shortly after fuel injection. The negative heat release is observed for the two fuels during a major part of the ignition delay.

2. The negative heat release is followed by very slow reactions causing a slight increase in the rate of heat release. The end of the pressure rise delay measured from the pressure trace, coincides with the end of these slow reactions, before the start of the very high speed reactions.

The negative heat release period as well as the total ignition delay period are shorter for diesel no. 2 fuel than for CITE fuel. These results support the previous conclusions reached,[1*] that the activation energy for diesel no. 2 fuel is smaller than that for CITE fuel, causing the preignition reactions for the diesel fuel to be faster and the delay period shorter than for the CITE fuel.

The ignition delay is followed by a period of very rapid or explosive type reactions during which the energy of reaction of the fuel is released. These reactions occupied a relatively short period compared with the total ignition delay.

The maximum rate of heat release for the diesel fuel was found to be about 75% of that for CITE fuel.

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*Numbers refer to list of references.

B. EFFECT OF SPEED ON IGNITION DELAY, SMOKE, WALL TEMPERATURE, AND THERMAL LOADING

1. Effect of Engine Speed on Ignition Delay

The apparent effect of the increase in engine speed is to decrease the ignition delay. However, if a correction is made for the effect of increase in the charge temperature with speed, the ignition delay was found to increase with speed. The conditions of the tests carried out to study the effect of speed on ignition delay were carefully adjusted to eliminate the change in any parameter other than the engine speed.

2. Effect of Speed on Smoky Intensity

An increase in speed from 1500 rpm and 3000 rpm caused an increase in the smoke intensity from 40 to 60 Hartridge units.

3. Effect of Speed on Wall Temperatures

The increase in speed produced the following effects in the wall temperature at the different locations in the cylinder head.

a. The wall surface temperature in the valve bridge of the fire deck increased at a high rate with the increase in speed from 1000 rpm to 2000 rpm, after which the temperature leveled off. At 1000 rpm the surface temperature was 435°F and reached 509°F at 2900 rpm.

b. The swing in the surface temperature decreased from 37°F at 1000 rpm to 13°F at 2900 rpm.

c. The wall temperature at the midpoint between the gas side and coolant side in the fire deck showed a different trend.

   (1). near the exhaust valve the temperature increased from 326°F at 1000 rpm to 360°F at 2900 rpm.

   (2). near the inlet valve the temperature remained constant at about 267°F.

4. Effect of Speed on Thermal Loading

The thermal loading which is equal to the sum of the heat lost to the water jackets and lubricating oil increased with speed. However, the thermal loading as a percentage of the heat input in the fuel decreased from 20% at

1000 rpm to 14% at 2900 rpm.

C. EFFECT OF COOLANT TEMPERATURE ON COMBUSTION PHENOMENA

1. Effect of Coolant Temperature on Ignition Delay

The increase in the coolant temperature from 156°F to 305°F did not affect the ignition delay. The value of $I.D._p$ over the whole temperature range at a mean pressure of 700 psia was 0.680 millisecond.

2. Effect of Coolant Temperature on Thermal Loading

The increase in coolant temperature reduced the percentage heat loss to the coolant and lubricating oil from 17.7% at 156°F to 13.8% at 305°F. The total heat loss decreased from 1660 Btu/hp. hr. at 156°F to 1230 Btu/hp. hr. at 305°F.

3. Effect of Coolant Temperature on After Injection

The increase in coolant temperature caused the after injection to decrease till a temperature of about 230°F, after which it increased again.

VI. PROBLEM AREAS AND CORRECTIVE ACTIONS

A. FUEL LEAKAGE PAST PUMP-PLUNGER

Problem: Excessive leakage of CITE fuel past the pump plunger and dilution of the lubricating oil in the sump.

Corrective Action: A new pump was installed.

B. FAILURE OF PRESSURE TRANSDUCER

Problem: Failure of fuel line pressure transducer type 601H.

Corrective Action: To avoid any delay in the progress of the experimental work a dummy transducer was made and installed.

C. SURFACE THERMOCOUPLE FAILURES

Problem: Failure of surface thermocouple.

Corrective Action: Design and manufacture of a new adaptor to relieve the tightening stress in the thermocouple body. The assembled body of a new thermocouple and adaptor were installe d in the cylinder head with the thermocouple surface flush with the inside wall surface.

D. ENGINE VIBRATION

Problem: Excessive vibration of the engine was noted at high speeds (above 2800 rpm).

Corrective Action: The balancing weights were checked and the left balancing shaft found 90° ahead of the position indicated in the drawings. The front plate of the auxiliary drive was taken off and the shaft position adjusted to conform with the engine specifications.

VII. FUTURE PLANS

A. NEXT PERIOD

1. Experimental. Run tests on ATAC open chamber engine to find the effect of anti-smoke additives on the ignition delay and the rate of heat release.

2. Publication of part of the results in national meetings. To prepare a paper to be presented to the SAE on "Correlation of the Air Charge Temperature and Ignition Delay for Several Fuels in a Diesel Engine." Permission for this publication has been requested from ATAC.

B. OVERALL

1. Experimental. To complete the runs on the effect of gas pressure on the ignition delay and other combustion phenomena.

2. Analytical. To study the effect of pressure on the ignition delay, and to compare the results obtained on the ATAC engine and the results of previous work done in bombs and engines.

VIII SIGNIFICANT ACCOMPLISHMENTS

The paper presented before the Society of Automotive Engineers in January, 1967, covering the experimental results on the Lister-Blackstone engine will be published in the SAE Transactions of 1968. The title of this paper is "Ignition Delay in Diesel Engines," by the authors of this report.

The computer programs made for the calculation of the rates of heat release proved to be successful. The results reached reflect the accuracy with which the experimental and analytical data have been taken.

These computer programs are now ready to study the effect of fuel additives on the combustion process and rates of heat release.

PART II

INSTRUMENTATION, EXPERIMENTAL, AND ANALYTICAL RESULTS

Additional instrumentation made during this reporting period has included means to measure the wall temperatures, thermal loads on the cooling and lubricating systems, including the high coolant temperature running conditions.

The experimental and analytical results covered the following areas:

A. Heat release computations and results.

B. Effect of speed on ignition delay and other combustion phenomena.

C. Effect of coolant temperature on ignition delay and other combustion phenomena.

I. INSTRUMENTATION

During this period the engine was instrumented to measure the following:

A FIRE DECK WALL TEMPERATURE

The temperature of the metal midway between the gas and coolant sides of the fire deck was measured by an iron-constantan thermocouple. Two thermocouples were used, to measure the temperature at a radial distance of 1/8 in. from the exhaust the inlet valve inserts. The position of these thermocouples is shown in Fig. 1.

B. COOLANT FLOW RATE

The cooling system piping was changed to allow the use of a closed system with a heat exchanger, as shown in Figs. 2 and 3. The coolant flow rate was measured by a standard ASME sharp edge orifice as shown in Fig. 4. The coolant used was ethylene-glycol.

C. TEMPERATURE RISE OF COOLANT ACROSS THE ENGINE

The rise in the coolant temperature from its entrance to the exit from the engine was measured by two iron-constantan thermocouples. This temperature rise and the coolant flow rate were used to calculate the thermal load on the cooling system.

D. LUBRICATING OIL FLOW RATE

The rate of flow of the lubricating oil was measured by a turbine type meter. The oil was cooled in a heat exchanger to a constant temperature of 200°F. The oil cooling system is shown diagramatically in Fig. 5.

E. TEMPERATURE DROP ACROSS THE OIL COOLER

The increase in oil temperature across the engine was measured by two iron-constantan thermocouples. This was used to calculate the thermal load on the lubricating system.

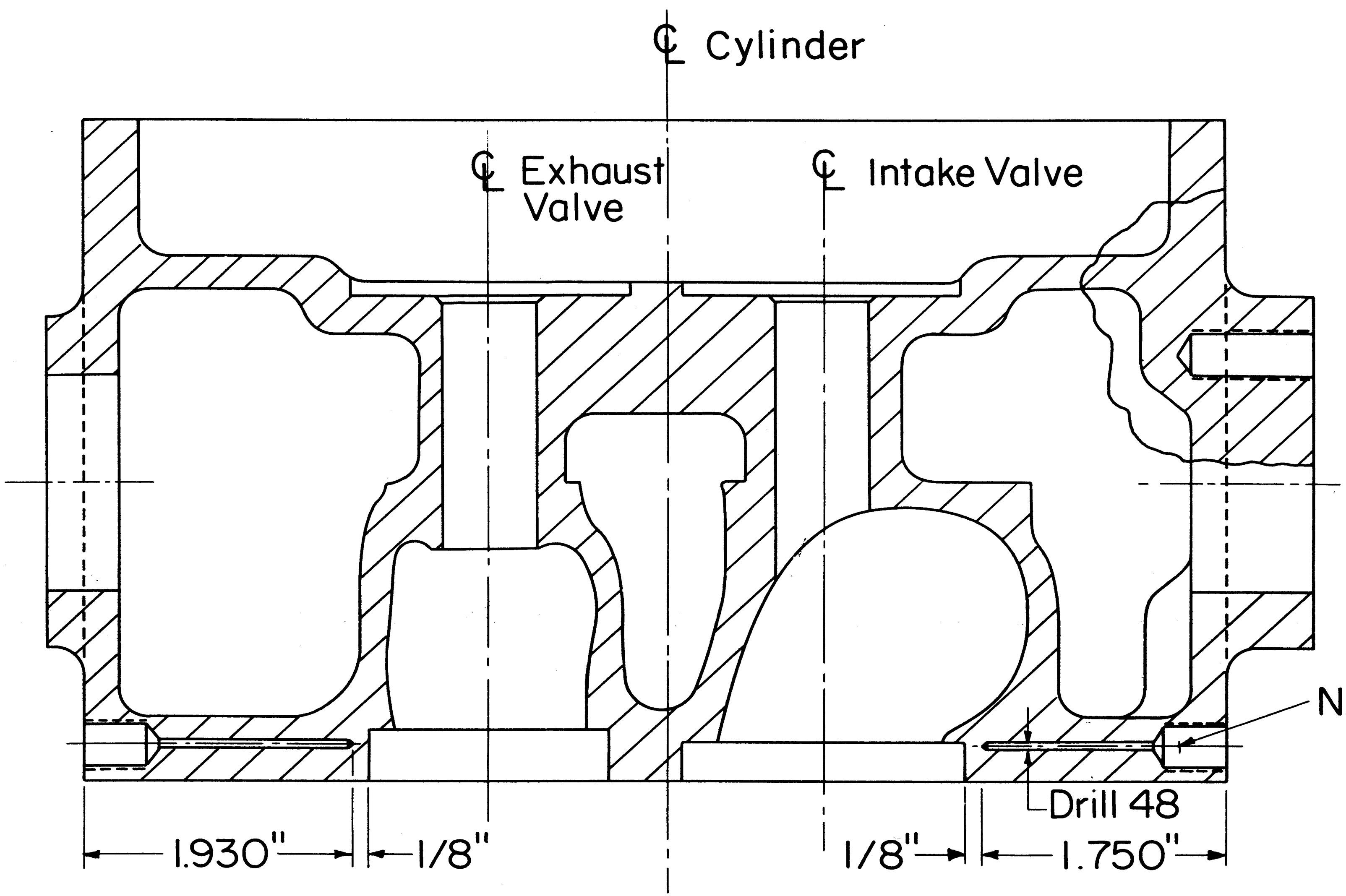


Fig. 1. Position of thermocouples in the fire deck near the intake and exhaust valve seats.

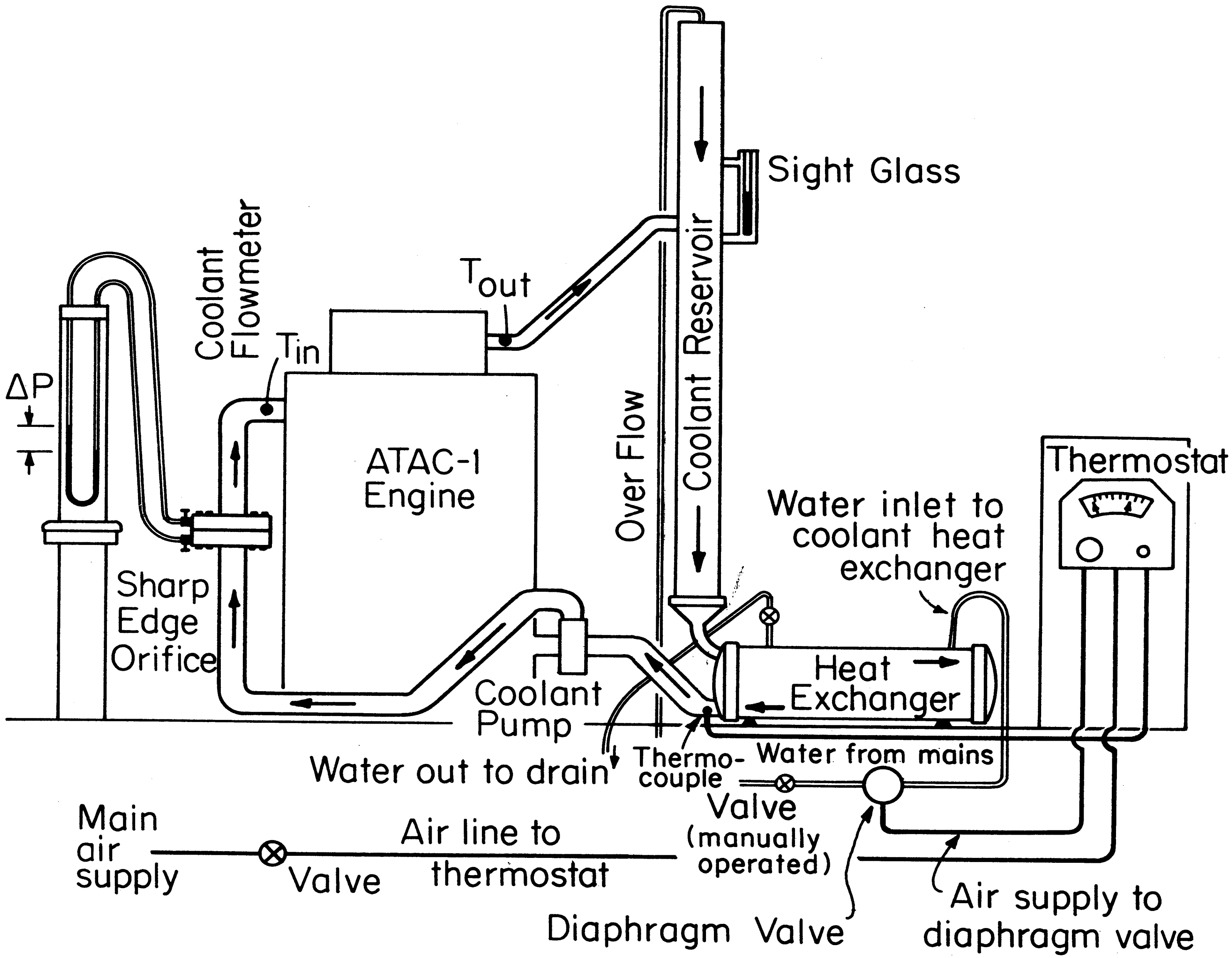


Fig. 2. Closed cooling system for the use of ethylene-glycol at high temperatures.

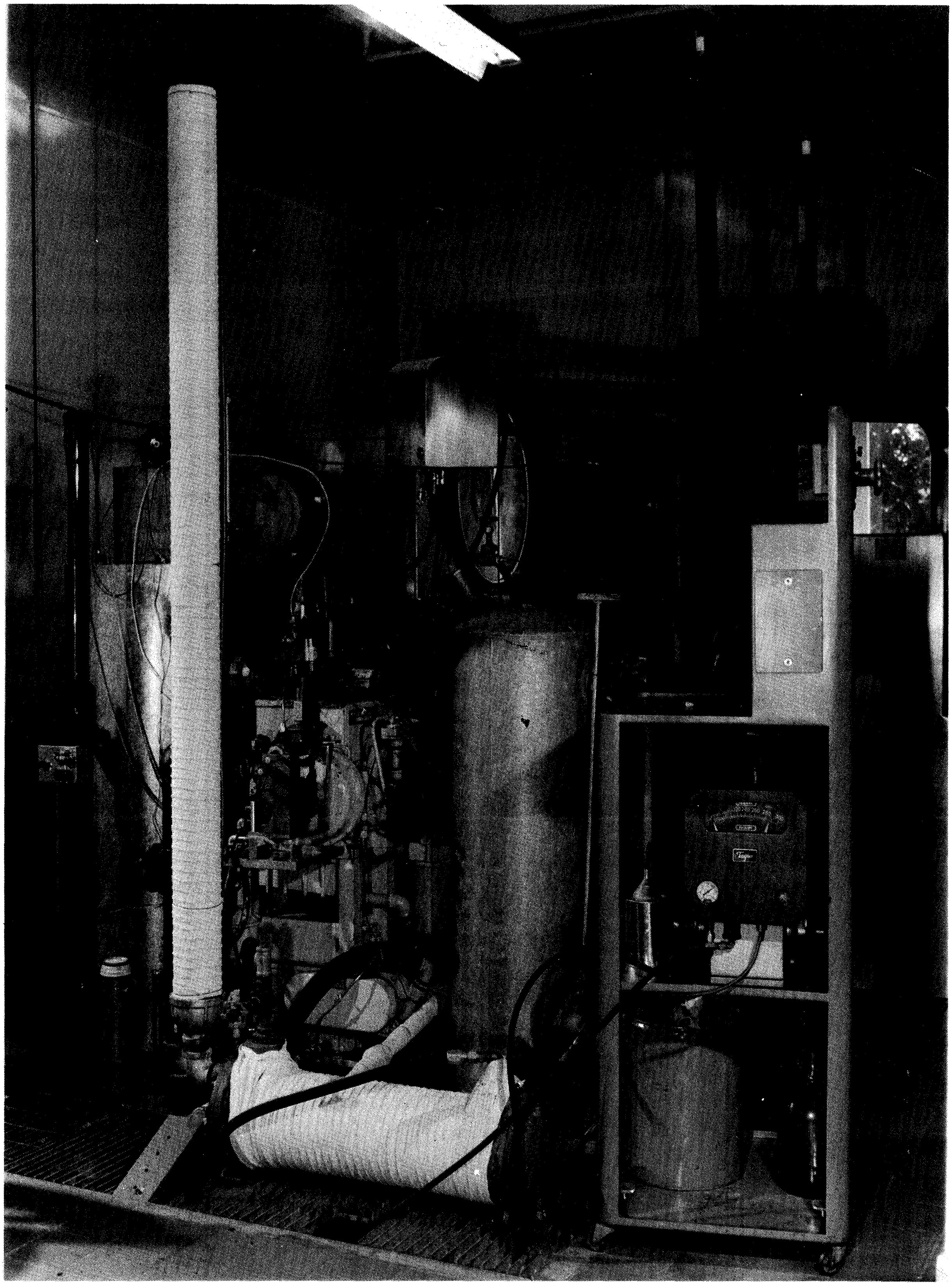


Fig. 3. Photograph of the closed cooling system for ATAC-1 engine.

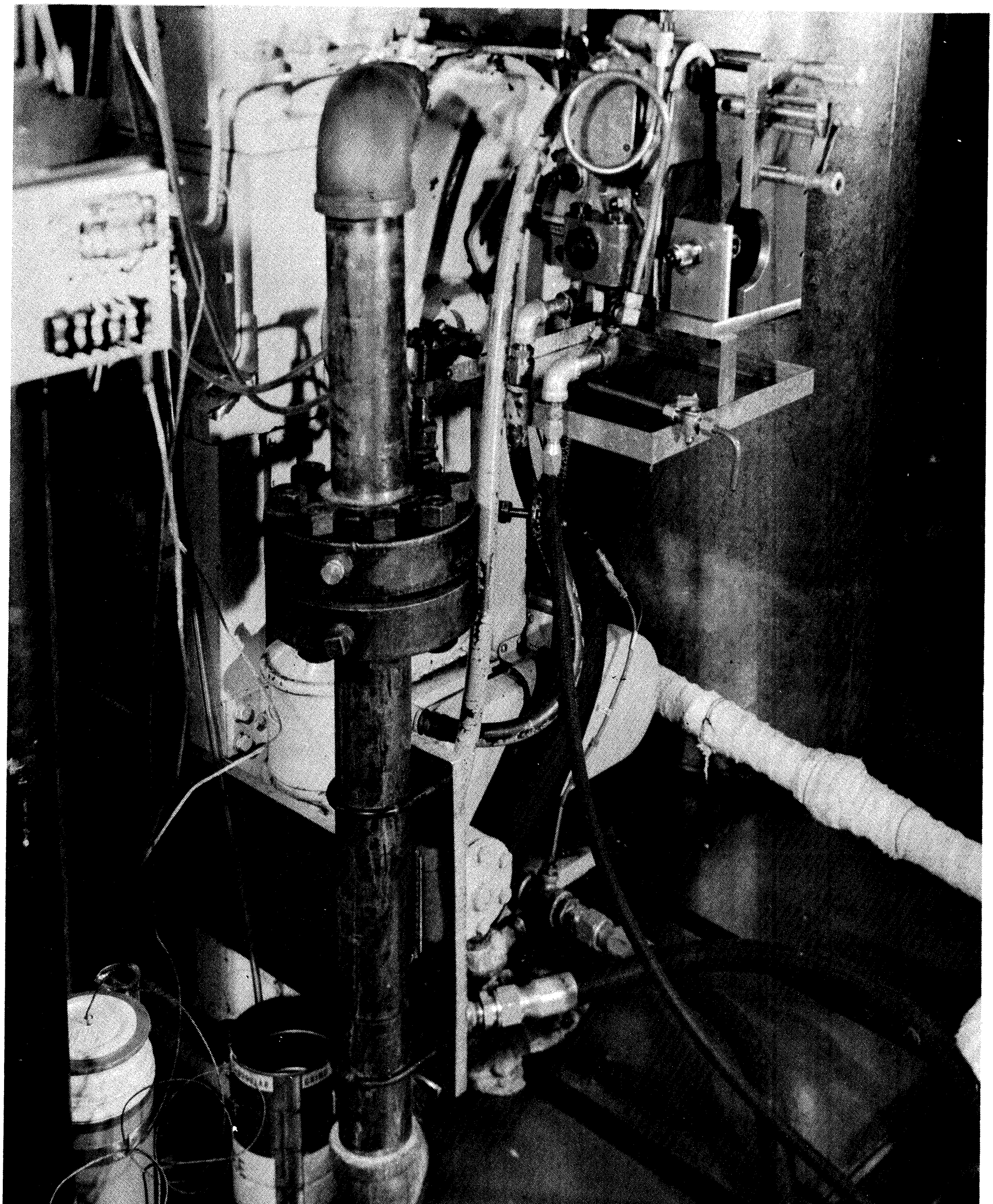


Fig. 4. Photograph of the coolant flow meter.

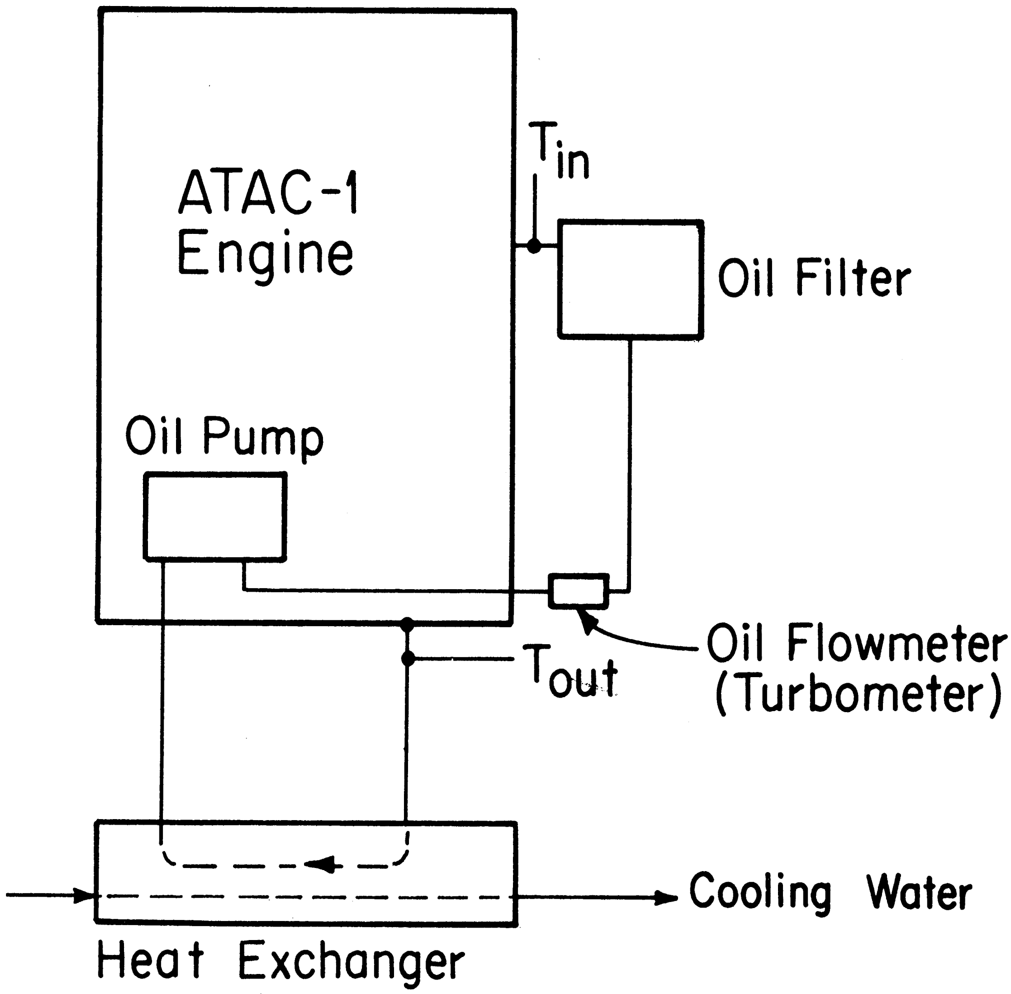


Fig. 5. Lubricating oil cooling system.

II. HEAT RELEASE COMPUTATIONS AND RESULTS

The rate of heat release in the ATAC engine, during the combustion process was calculated for diesel no. 2, and CITE fuels, under the following running conditions:

Fuel	Diesel No. 2	CITE (Mil-F-45121)
Pressure in surge tanks, in. Hg absolute	29.3	29.4
Inlet air temperature, °F	96.0	94.0
Fuel-air ratio	0.0301	0.0299
Injector opening pressure, psia (static)	3000.0	3000.0
Injector timing, (dynamic) degrees before T.D.C.	20.2	20.3
Engine speed, rpm	2001.0	2000.0
Coolant temperature at outlet, °F	174.0	170.0

The following traces were observed on the oscilloscope screen and photographed by the polaroid camera.

a. Gas pressure—crank angles

b. Fuel pressure—crank angles

c. Needle lift—crank angles

d. Surface wall temperature—crank angles

The gas pressure—crank angles trace was taken for the whole cycle and for successive divisions of the cycle. The duration of each division depend on the events taking place in the cycle during this division. In some cases a photograph was taken for the details of the pressure trace over a period of six or nine crank angles only during the ignition delay and the rapid pressure rise periods. The gas pressure at any crank angle was calculated from these traces by a statistical adjustment of the values obtained from the sequence of pressure traces and that from the trace for the whole cycle.

The statistically adjusted values were used to plot the pressure trace for the whole cycle or any part of it by the computer. A sample trace for the pressure trace plotted by the computer for the engine running on CITE fuel is shown in Fig. 6. The points shown on this trace correspond to the reference points on the pressure trace taken for the whole cycle.

The corresponding traces plotted by the computer for the needle lift and fuel pressure are shown in Fig. 7. It shows that the needle lift started at 20.3° before T.D.C., when the fuel pressure was 3650 psia. The fuel pressure reached a maximum value of 4200 psia at 18.3° crank angles before T.D.C., while the needle lift was 2/1000 in. After this point the fuel pressure dropped due to the discharge of the fuel into the cylinder. The maximum needle lift was 15.3/1000 in., at an angle of 13.5° before T.D.C. The needle was completely closed, at zero lift, at an angle of 7.4° before T.D.C. At this crank angle the fuel pressure was about 1550 psia. The fluctuations in the needle lift trace after its closure are due to the bouncing of the needle on its seat.

The theoretical rate of fuel injection was calculated from the equivalent area for fuel flow, the difference between the fuel and gas pressures. The coefficient of discharge was assumed constant during the injection period and was computed from the ratio of the actual fuel consumption and the theoretical accummulated fuel. The equivalent area for fuel flow was calculated from the needle seat area and the holes area, as shown plotted in Fig. 23 and tabulated in Table 4.

The rate of fuel injection, the accummulated fuel injection, and the percentage of injected fuel are shown plotted by the computer in Fig. 8. The maximum rate of fuel injection was 370 lb per hour at an angle of 15.5° before T.D.C. At this location only 32% of the total fuel injection was accummulated in the cylinder. When the needle was first closed, 95% of the fuel was injected into the cylinder. This means that the after injection amounted to 4% of the total fuel. In this test the end of the pressure rise delay was at 4.5° before T.D.C. after almost all the fuel has been injected into the cylinder. The total amount of fuel injected per cycle is 79.5×10^{-6} lbm.

The detailed pressure trace during the ignition delay and the rest of the combustion process is shown in Fig. 9. The pressure fluctuations in this trace, near the maximum pressure, were smoothed by taking their averages, and used for the heat release computations. The heat release diagram calculated for this cycle is shown in Fig. 10. This figure shows that the preignition reactions occur in two distinct stages:

1. The first stage from the start of injection at 20.3° before T.D.C. to 6° before T.D.C. During this stage negative heat release occurs and is believed to be due to the fuel evaporation and the endothermic reactions.

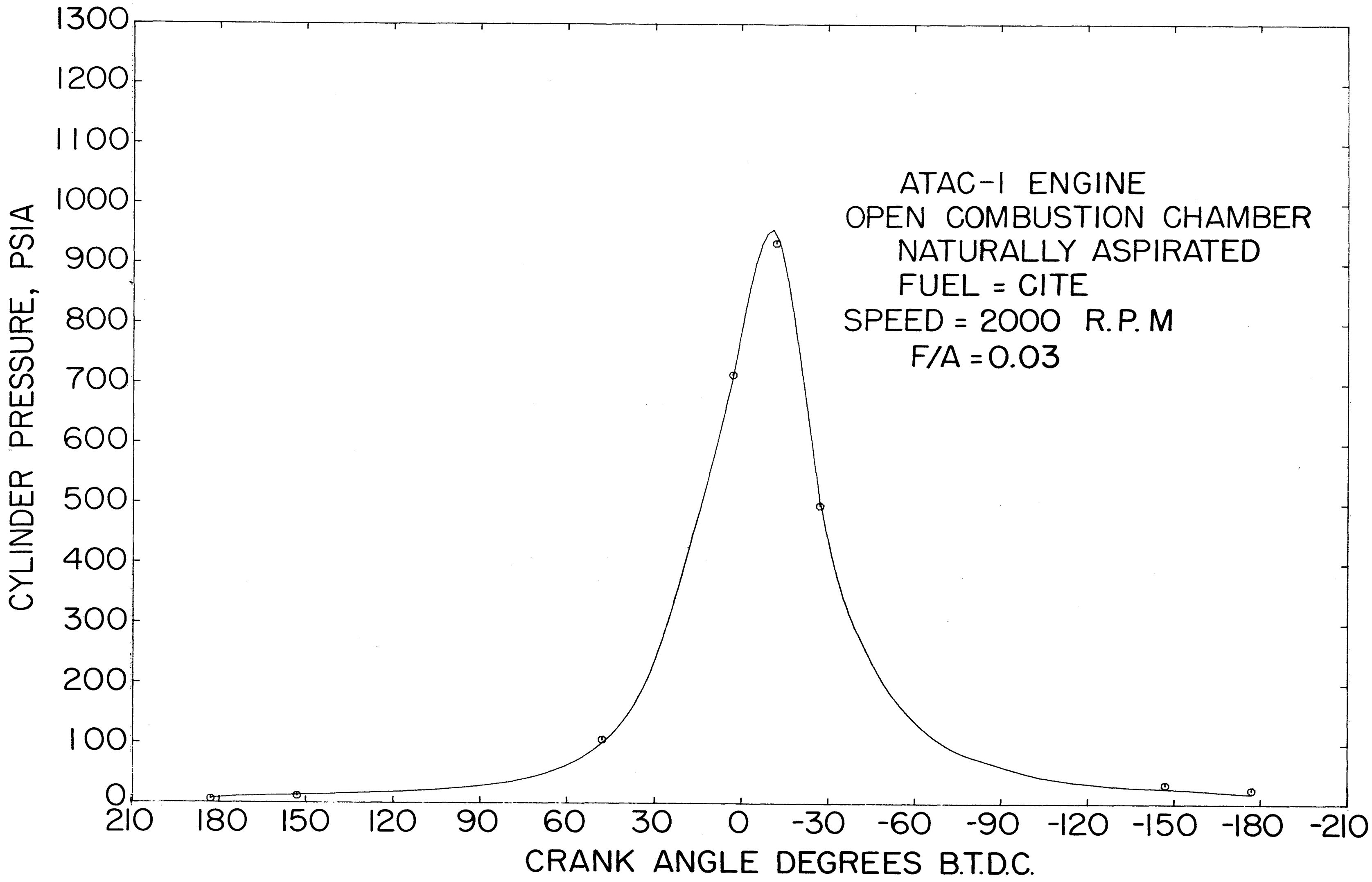


Fig. 6. Pressure trace for ATAC-1 engine plotted by the computer.

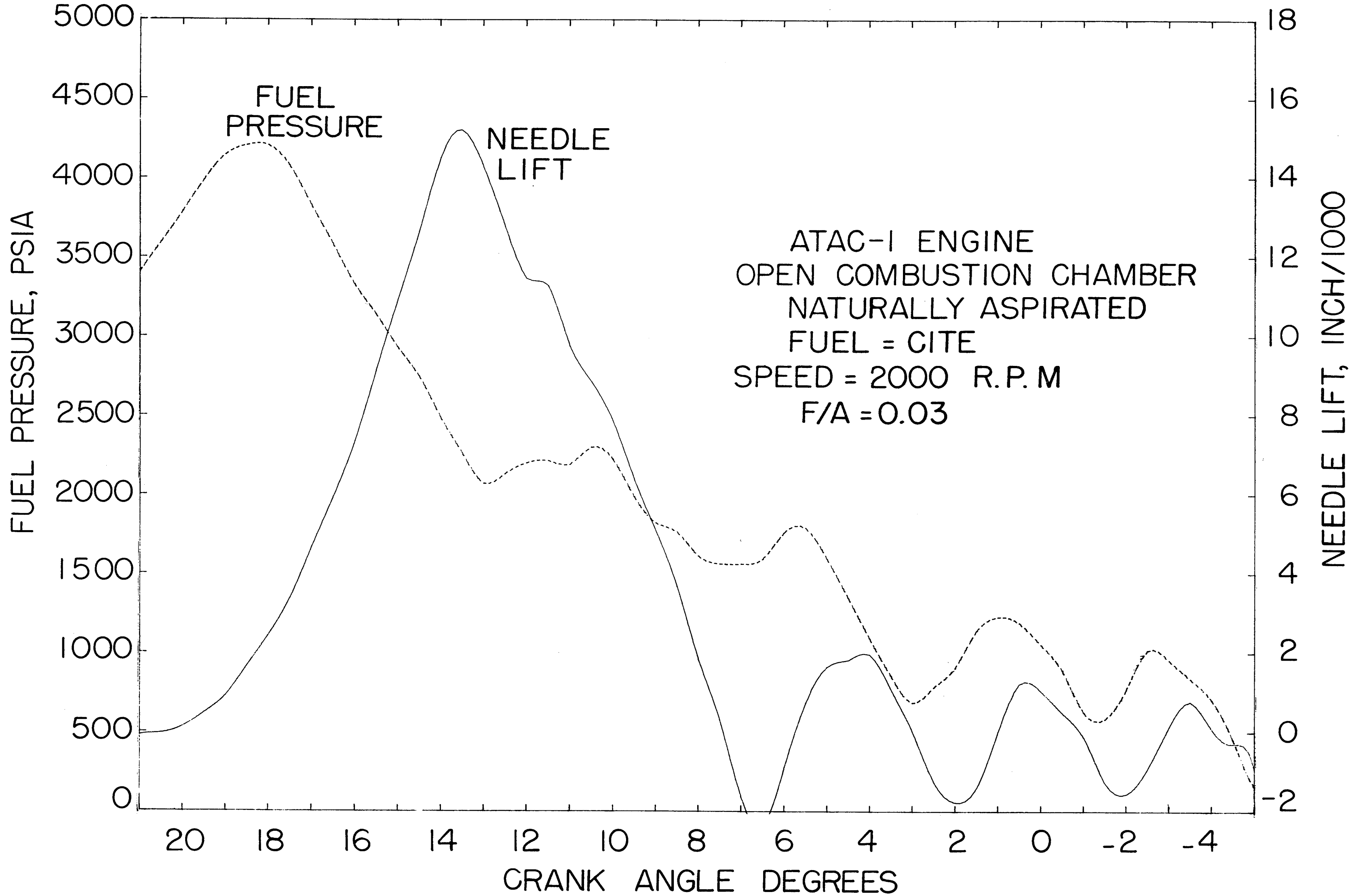


Fig. 7. Fuel pressure and needle lift traces for ATAC-1 engine plotted by the computer.

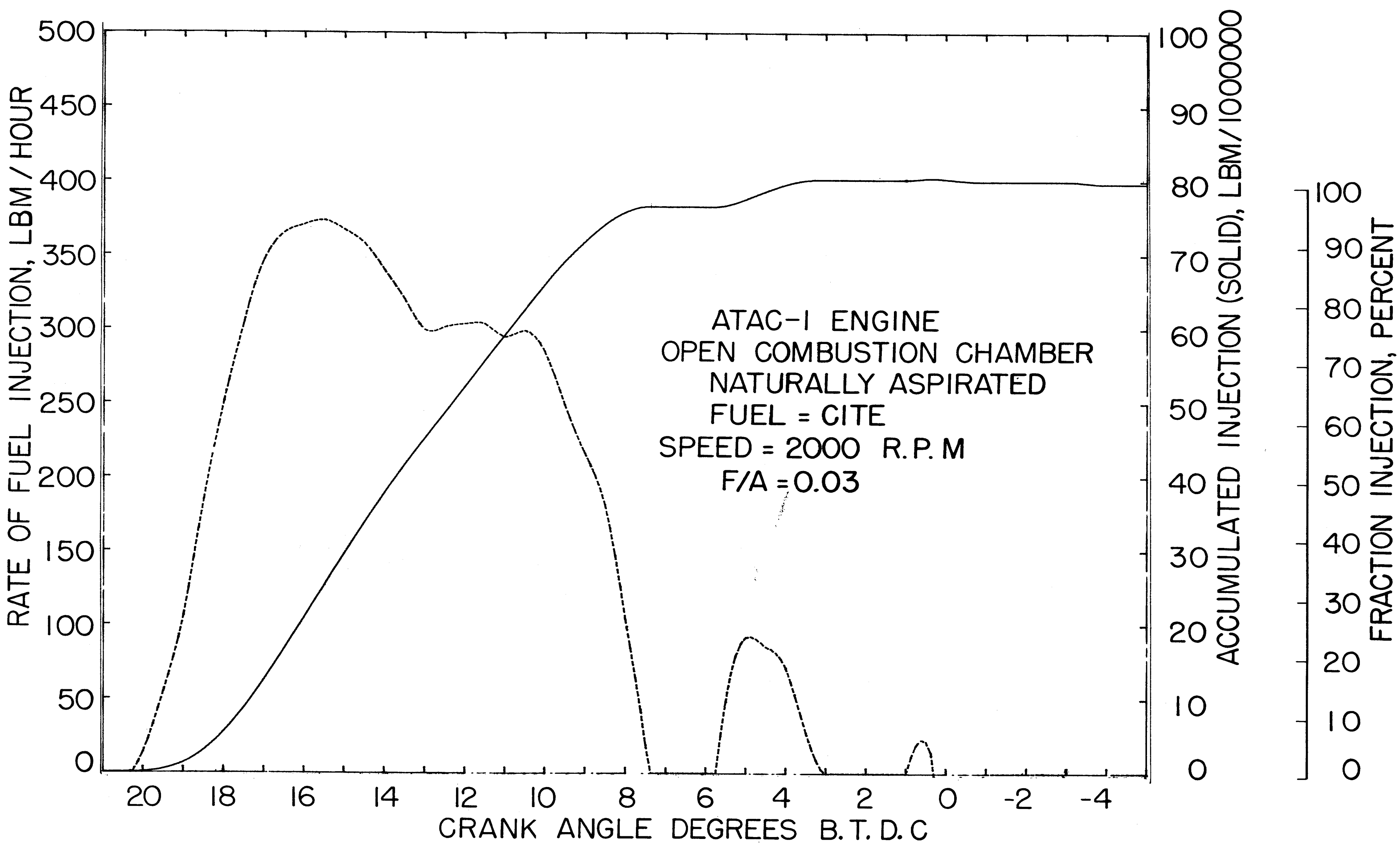


Fig. 8. Rate and accumulated fuel injection for ATAC-1 engine plotted by the computer.

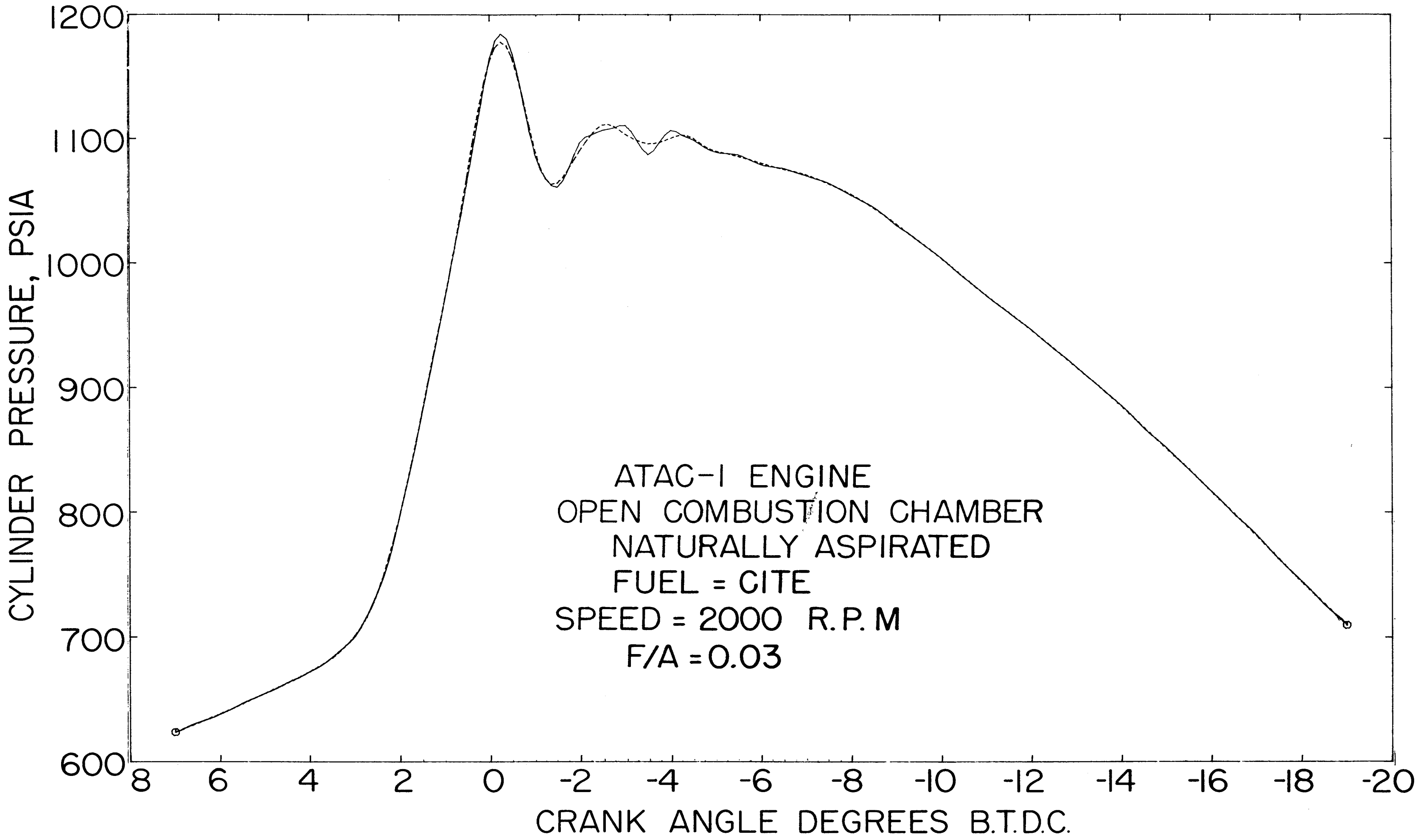


Fig. 9. Detailed pressure trace for ATAC-1 engine during combustion.

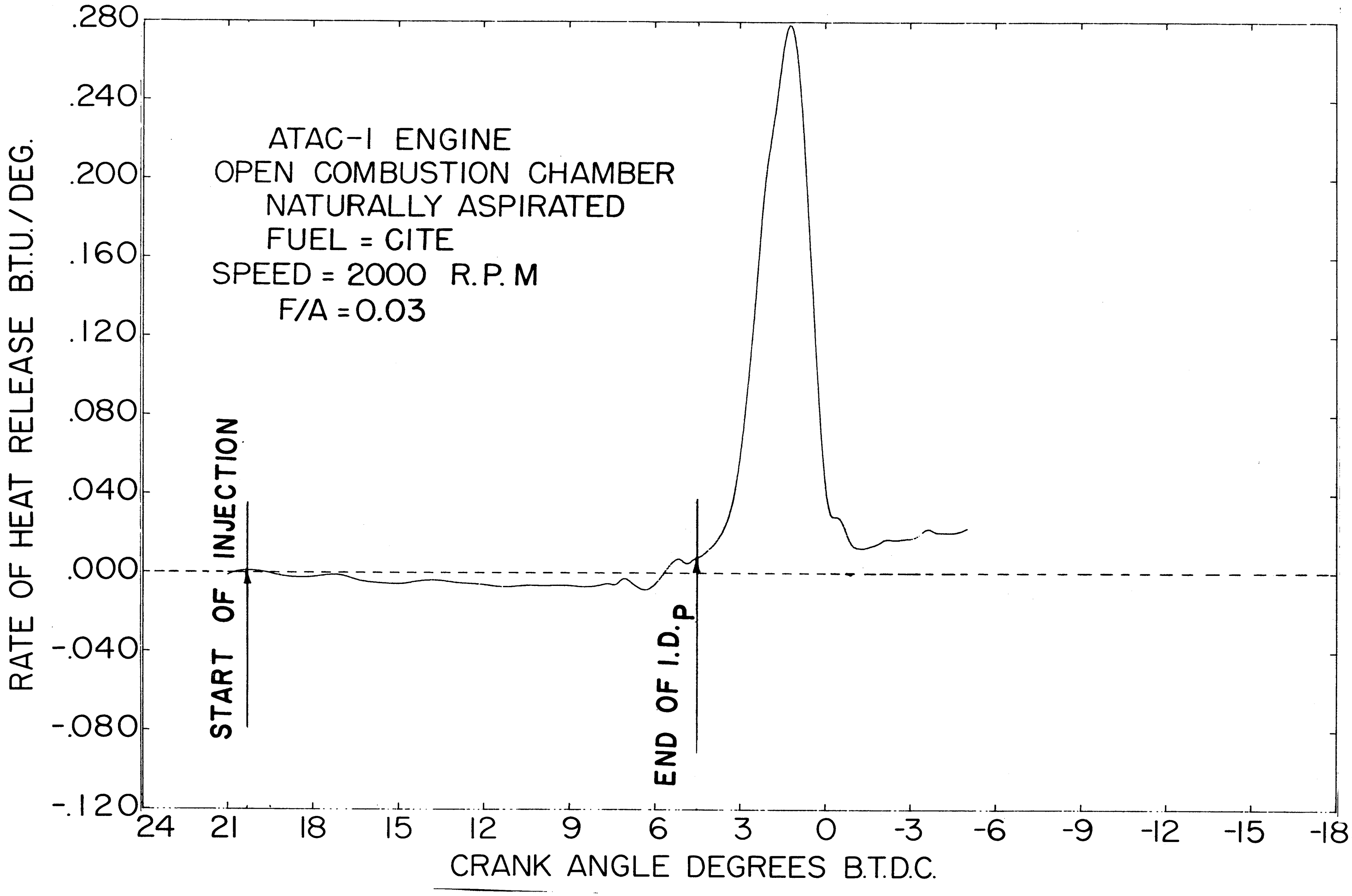


Fig. 10. Heat release diagram for ATAC engine with CITE fuel plotted by the computer.

2. The second stage is from 6° B.T.D.C. to 4.5° B.T.D.C., during which very slow reactions occur resulting in a small rate of heat release. These slow reactions are followed by explosive type reactions, resulting in a maximum rate of heat release of 0.28 Btu per crank degree. It is interesting to note that the ignition delay period was 15.8°, while the following rapid combustion process lasted only for about 4.5°.

The two stage preignition reactions were also observed in the heat release diagram for diesel no. 2 fuel shown in Fig. 11. In this case the ignition delay was shorter and the maximum rate of heat release was 0.21 Btu per crank degree, or 75% that of CITE fuel. The two stage preignition reactions in the combustion of hydrocarbon fuels were observed by other investigators as Jost,[2] Andreev,[3] and Aivagov and Neumann.[4]

COMPUTER PROGRAMS MADE FOR THE HEAT RELEASE CALCULATIONS

The following computer programs were used for the cycle analysis and heat release computations made for the ATAC engine.

Program No. 1: Heat release calculations

Program No. 2: Sequencial cycle data analysis

Program No. 3: Curve fitting

Program No. 4: Cylinder volume and gradient

Program No. 5: Cylinder gas properties

Program No. 6: Engine data reading and printing

Program No. 7: Engine data calculations

The detail of each of these programs is given in Appendix A.

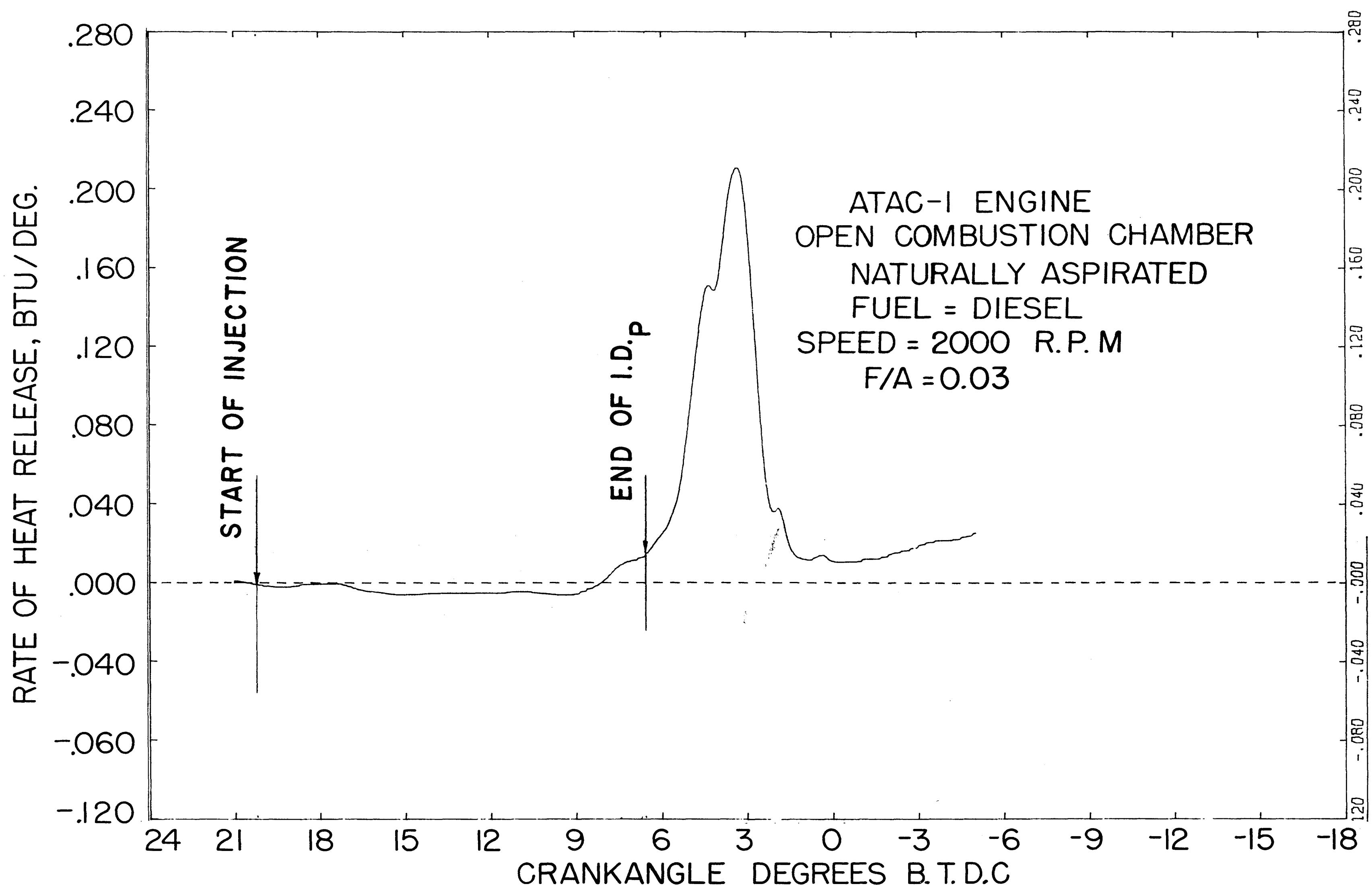


Fig. 11. Heat release diagram for ATAC engine with diesel no. 2 fuel plotted by the computer.

III. EFFECT OF SPEED ON IGNITION DELAY AND OTHER COMBUSTION PHENOMENA

To study the effect of speed on ignition delay and the other combustion phenomena, two series of runs were made, covering a speed range from 1000 rpm to 2900 rpm. One of these series was at a mean pressure of 500 psia and the other at 700 psia.

The change in engine speed was found to cause changes in other parameters that affect the combustion process, like cylinder pressure and temperature, and injection timing. To study the effect of speed alone on the combustion phenomena, experimental adjustments were made to eliminate the effect of these parameters or to correct for their effect on ignition delay. The injection timing was manually adjusted so that the needle lift would start at a constant crank angle before the T.D.C., at all engine speeds. The mean cylinder pressure during the ignition delay was kept at a constant value of 500 psia or 700 psia, by changing the pressure in the surge tank. The effect of the change in the mean temperature during the ignition delay was corrected for by using a correction formula based on the previous experimental results on the ATAC engine, with the same fuel under the same mean pressure during the ignition delay.

A1. EFFECT OF SPEED ON $I.D._p$ AT MEAN PRESSURE = 500 psia

Conditions of Test

Fuel: CITE refree grade (Mil-F-45121 fuel)

Mean pressure during $I.D._p$ = 500 psia

Inlet air temperature = 80°F

Fuel-air ratio = 0.0315

Injector opening pressure = 3000 psia

Injection timing (start of needle lift) = 20.9° B.T.D.C.

Cooling water at outlet = 176°F

Variables

Engine speed: from 1000 to 2800 rpm

Inlet air surge tank pressure: from barometric to 10.7 in. Hg boost

Results

The effect of speed on ignition delay is shown in Fig. 12. The measured pressure rise delay $I.D._p$ decreased from 1.567 millisec at 1000 rpm to 1.149 millisec at 2800 rpm. The illumination delay $I.D._{1L}$ was always longer than the pressure rise delay, and decreased from 1.883 millisec at 1000 rpm, to 1.525 millisec at 2800 rpm. Under the test conditions the observed change in ignition delay with engine speed is due to variations in air velocity and air temperature. To eliminate the effect of the change in the air temperature on ignition delay, a correction formula based on Arrhenius equation was used.

$$\frac{I.D._{corrected}}{I.D._{measured}} = e^{\left[\frac{E}{R_u}\left(\frac{1}{T_{ref.}} - \frac{1}{T_m}\right)\right]} \tag{1}$$

where

E = activation energy

R_u = universal gas constant

$T_{ref.}$ = a reference temperature to which the ignition delay is corrected = 1619°

T_M = the mean temperature during ignition delay.

The value of the activation energy E was determined for CITE fuel under a mean pressure of 700 psia, and found equal to 10430 Btu/lb mole. The details of this work is given in Ref. 1. Upon using this value of E in Eq. (1), it was noticed that the corrected ignition delay increased with speed as shown in Fig. 13. Since this result seemed to be contrary to previously published data for the effect of speed on ignition delay, it was decided to repeat this series of runs with a mean pressure during the ignition delay at 700 psia, the pressure at which the activation energy was determined.

A2. EFFECT OF SPEED ON $I.D._p$, MEAN PRESSURE - 700 psia

Conditions as in A1, except that the mean pressure during $I.D._p$ = 700 psia.

Variables

Engine speed: from 1000 rpm to 2900 rpm

Inlet surge tank pressure: from 22.9 in. Hgg to 10.6 Hgg.

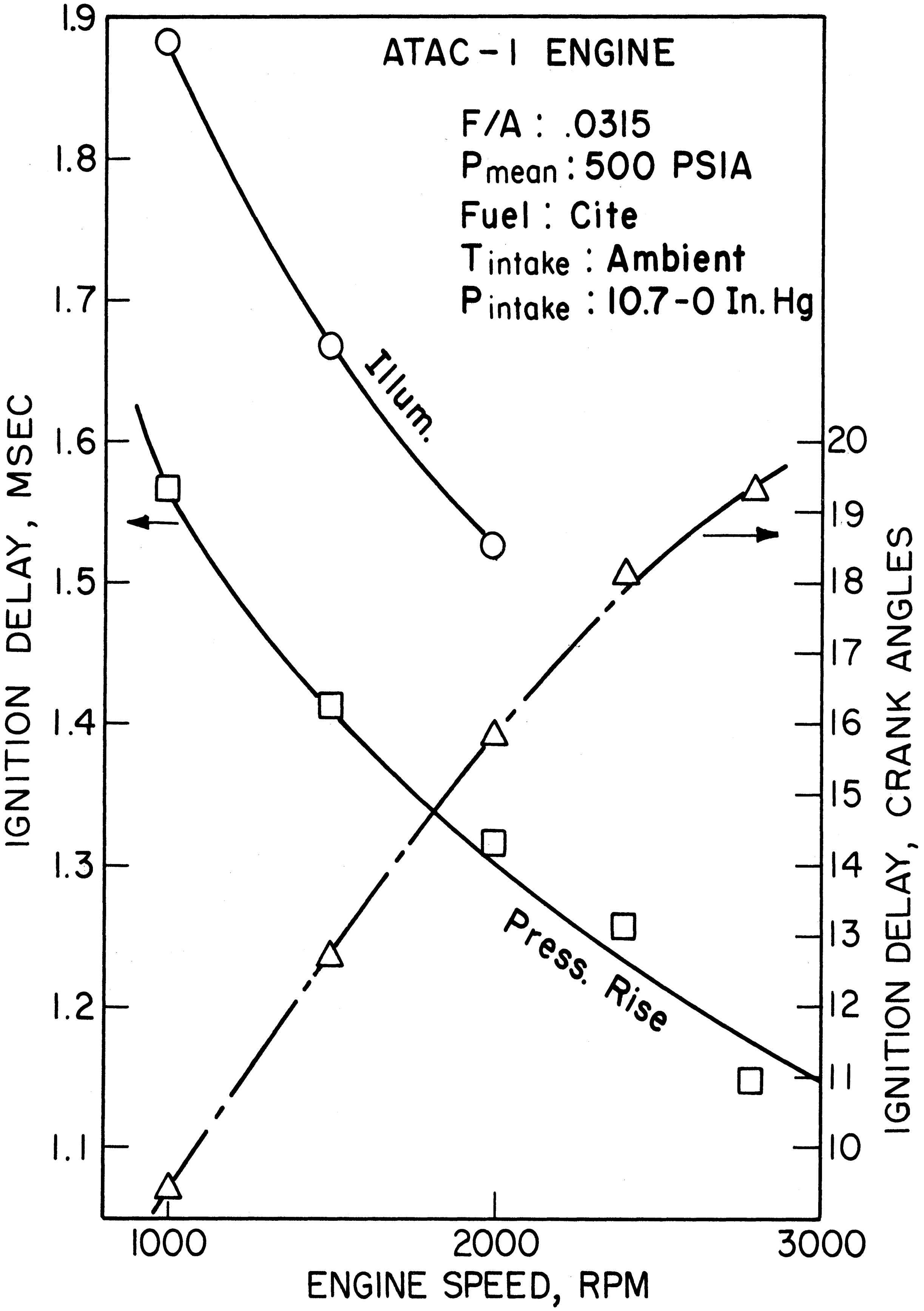


Fig. 12. Effect of engine speed on ignition delay at a mean pressure of 500 psia.

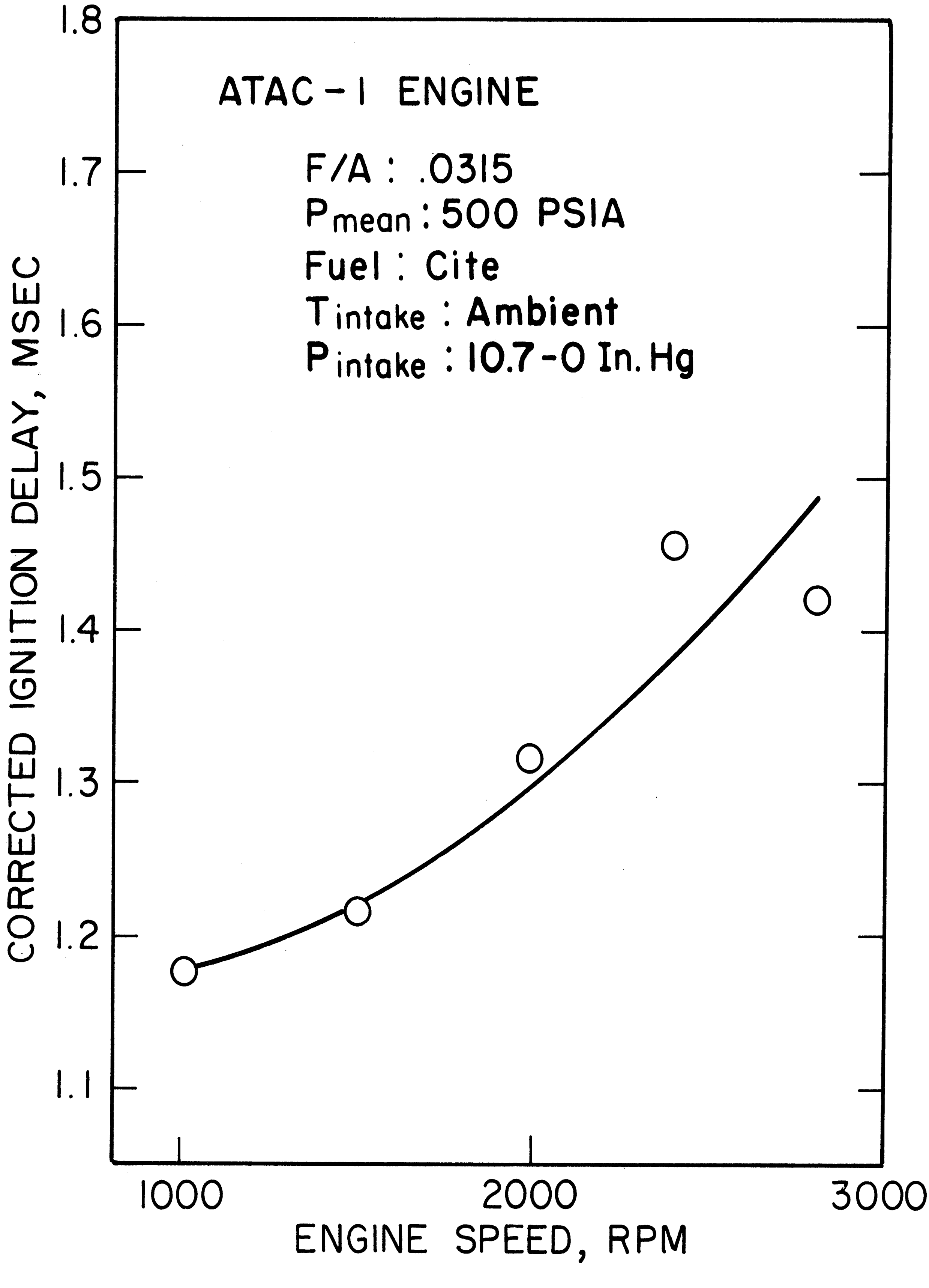


Fig. 13. Corrected ignition delay versus engine speed (reference temperature = 1619°R).

Under the above conditions the mean temperature during the ignition delay changed from 1436°R at 1000 rpm to 1707°R at 2900 rpm. The ignition delay was corrected for the change in temperature by using Eq. (1). The reference temperature, T_{ref}, was chosen to be the mean temperature during the ignition delay at 2000 rpm which is equal to 1557°R.

Results

Effect of speed on $I.D._p$. The results of the ignition delay in crank angle degrees and in milliseconds are plotted versus engine speed in Fig. 14. The ignition delay is 7.2° at 1000 rpm, and has increased to 15.9° at 2900 rpm. However, in terms of milliseconds, the ignition delay has dropped from 1.2 millisec at 1000 rpm, to 0.914 millisec at 2900 rpm.

The drop in the ignition delay with the increase in speed can be attributed to either the increase in turbulence with speed, or to the increase in the mean temperature during the ignition delay with speed.

The mean gas temperature, is shown in Fig. 15, increased from 1436°R at 1000 rpm, to 1707°R at 2900 rpm. This is an increase of 271°F. To correct for the effect of temperature on the ignition delay, Eq. (1) was used, and the results are plotted in Fig. 14. These values of ignition delay can be considered to be at the same mean temperature and pressure, and the only variable is the engine speed. From Fig. 14, it can be concluded that the increase in speed from 1000 rpm to 2900 rpm caused an increase in the ignition delay from 0.9 millisec to 1.23 millisec.

Similar observations concerning the increase in ignition delay with speed were reported by Small.[5]

The reason for the increase in the ignition delay with speed may be attributed to the increased leanness of the fuel-air mixture, in the region where combustion starts in the combustion chamber. Photographic studies on diesel combustion[6,7,8] showed that ignition starts in the pheriphery of the fuel spray, where the fuel droplets have access to the oxygen. The change in the mixture strength in this region is expected to affect the rate of reaction between the oxygen and fuel.

An increase in engine speed is expected to reduce the physical delay, which is the time required for the fuel to evaporate and form a combustible mixture. So if the physical parameters are the main controlling factors in the length of the ignition delay, it would be expected that an increase in engine speed would reduce the length of the ignition delay. However, the present experimental results show that the ignition delay increases with the speed. This might be an indication that the chemical processes, rather than the physical processes, are the main controlling factors on the ignition delay.

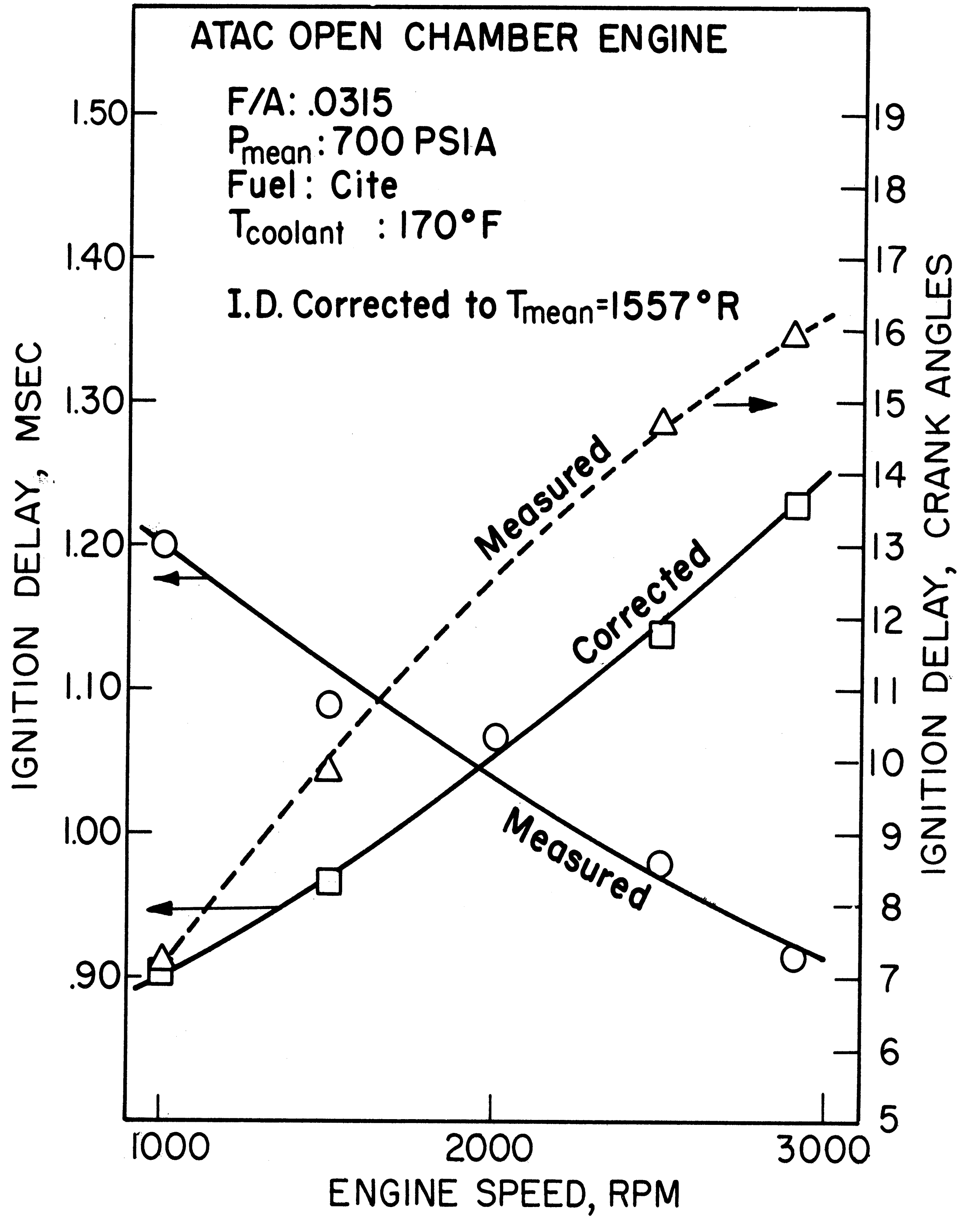


Fig. 14. Effect of engine speed on ignition delay at a mean pressure of 700 psia.

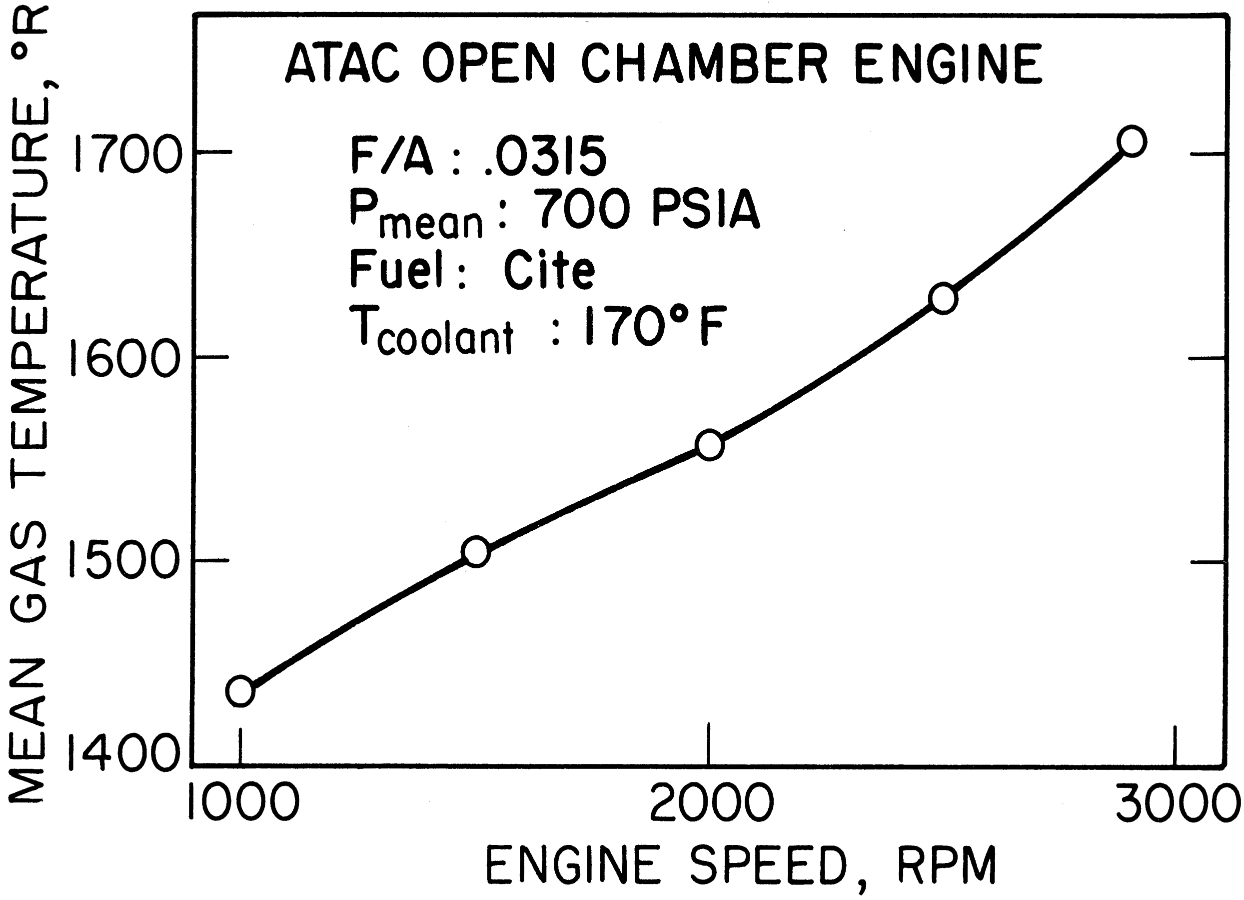


Fig. 15. Effect of speed on the mean gas temperature during the ignition delay.

B. EFFECT OF SPEED ON SMOKE INTENSITY

The results of smoke intensity in Hartridge Units are plotted versus engine speed in Fig. 16. Below 1500 rpm, there is one data point at 1000 rpm, which shows a heavy smoke intensity reading. The trend of change in smoke intensity between 1000 rpm to 1500 rpm cannot be concluded from the data point at 1000 rpm. But between 1500 rpm and 2900 rpm, the smoke intensity is shown to increase with speed. The increase in speed is expected to improve the mixing between the fuel and air, and increase the combustion efficiency. However, at higher speeds the time available for the chemical reactions to take place, at a certain temperature level, is reduced. Thus the carbon particles formed during the combustion process will have a shorter residence time, at the temperature below which they cannot combine with the oxygen.

From these experimental results it seems that the process of mixing is not the controlling process for carbon formation, but rather the temperature level and time available for the chemical reactions to take place are the main factors that affect carbon formation and removal, and thus the smoke intensity in the exhaust.

C. EFFECT OF SPEED ON COMBUSTION CHAMBER WALL TEMPERATURES

The wall temperatures are measured in the fire deck at three different locations:

1. The surface of the combustion chamber in the midpoint between the inlet and exhaust valves.

2. The wall temperature at a radial distance of 1/8 in. from the inlet valve insert, and 1/4 in. from the gas side.

3. The wall temperature at a radial distance of 1/8 in. from the exhaust valve insert, and 1/4 in. from the gas side.

The temperature of the fire-deck wall, at the three different locations, is plotted versus engine speed in Fig. 17.

The surface temperature in the valves bridge increased from 435°F at 1000 rpm to 509°F at 2900 rpm. The increase in surface temperature occurred between 1000 rpm and 2000 rpm, and was very little between 2000 rpm and 2900 rpm.

The wall temperature near the exhaust valve increased from 326°F at 1000 rpm to 360°F at 2900 rpm.

The wall temperature near the inlet valve was almost constant all over the whole speed range, at about 267°F.

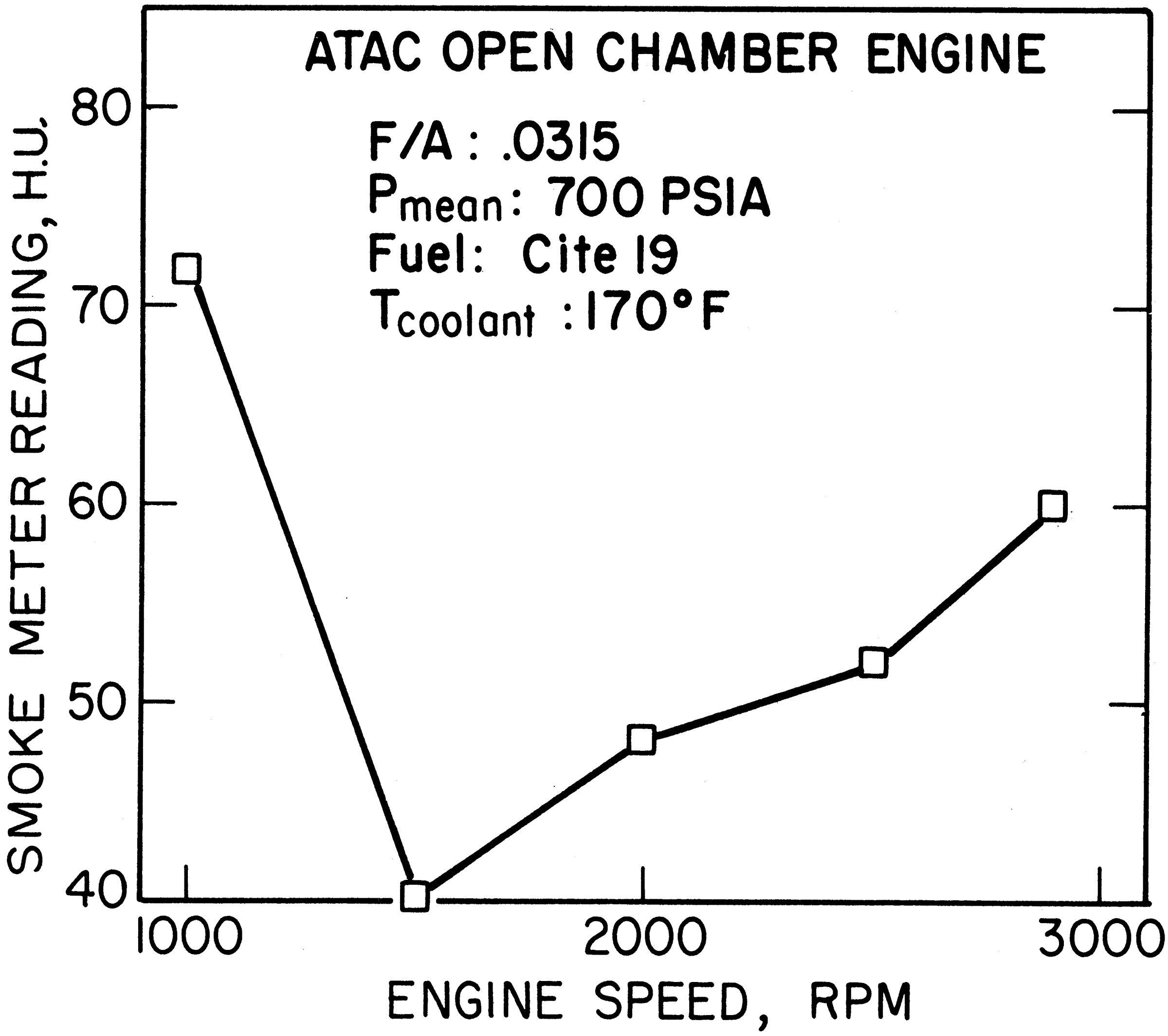


Fig. 16. Effect of speed on smoke intensity.

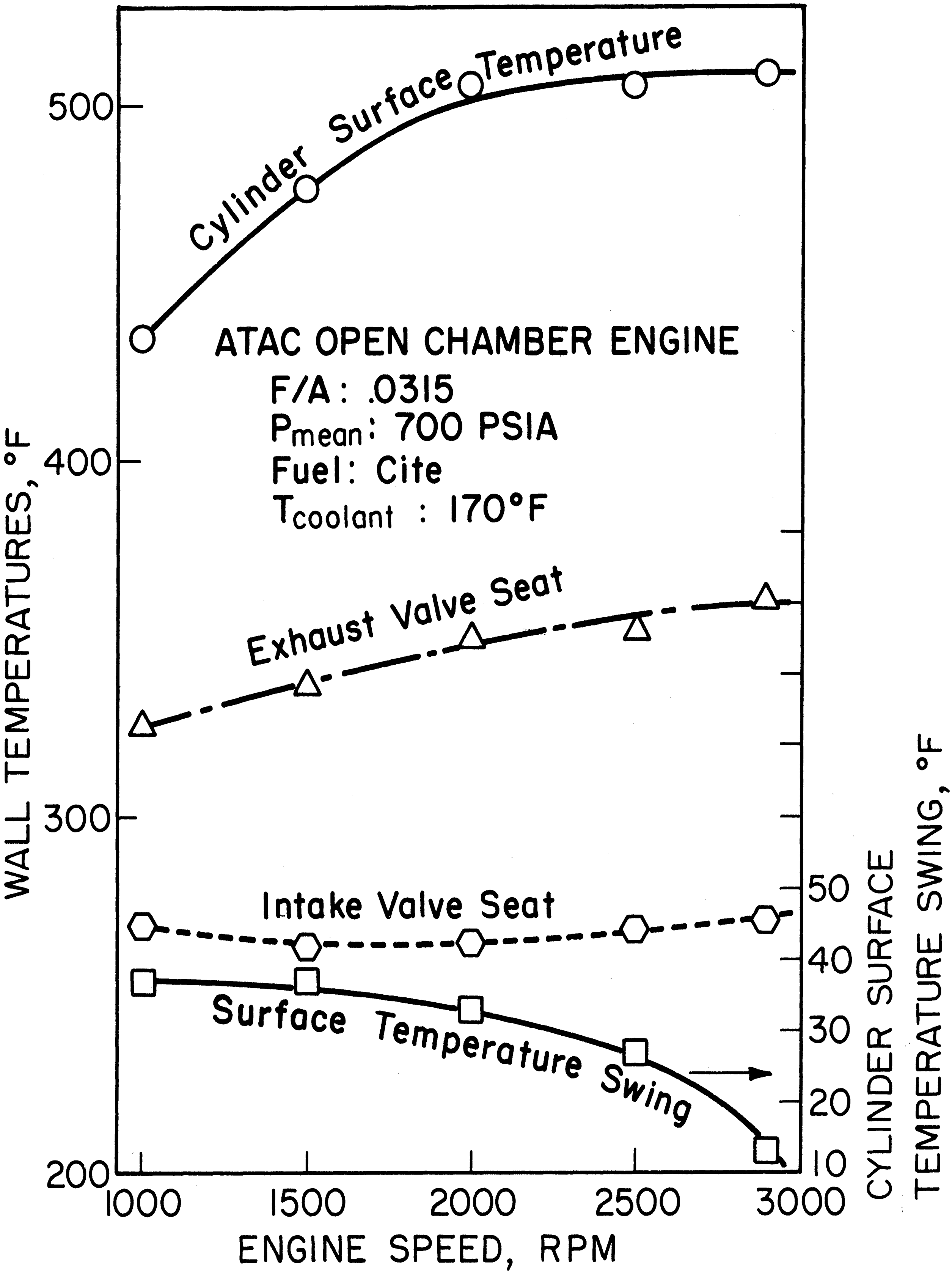


Fig. 17. Effect of engine speed on wall temperature.

The swing in the surface temperature decreased from 37°F at 1000 rpm to 13°F at 2900 rpm.

It is to be noted that all the above variations in temperature occurred with the following parameters kept at a constant value: fuel-air ratio, coolant temperature, injection opening pressure and timing, mean pressure during delay, and inlet air temperature. Thus the changes in the wall temperatures can be attributed only to changes in the heat transfer phenomena associated with engine speed.

D. EFFECT OF SPEED ON THERMAL LOADING

The heat lost from the gases to the combustion chamber walls, is transferred to the jackets cooling water or to the lubricating oil heat exchanger. Figure 18 shows that the heat lost to the water jackets increased slightly from 4.0 Btu/sec at 1000 rpm to 4.1 Btu/sec at 2900 rpm, and reached a maximum of 5.8 Btu/sec at 2500 rpm. The heat lost to the lubricating oil was 0.5 Btu/sec over a speed range from 1000 rpm to 2000 rpm, after which it increased gradually till it reached 2.8 Btu/sec, at 2900 rpm. The sum of the heat lost to the coolant and lubricating oil showed a continuous increase with speed.

The thermal loading as a percentage of the heat added in the fuel is plotted in Fig. 18. It shows an increasing trend in the percentage heat lost to the lubricating oil with speed. The percentage heat lost to the coolant and the total losses showed a continuous decrease with speed. About 20% of the heating value of the fuel is lost at 1000 rpm and it decreases to 14% at 2900 rpm.

The results of this series of runs are shown tabulated by computer in Appendix B, Tables 1 and 2.

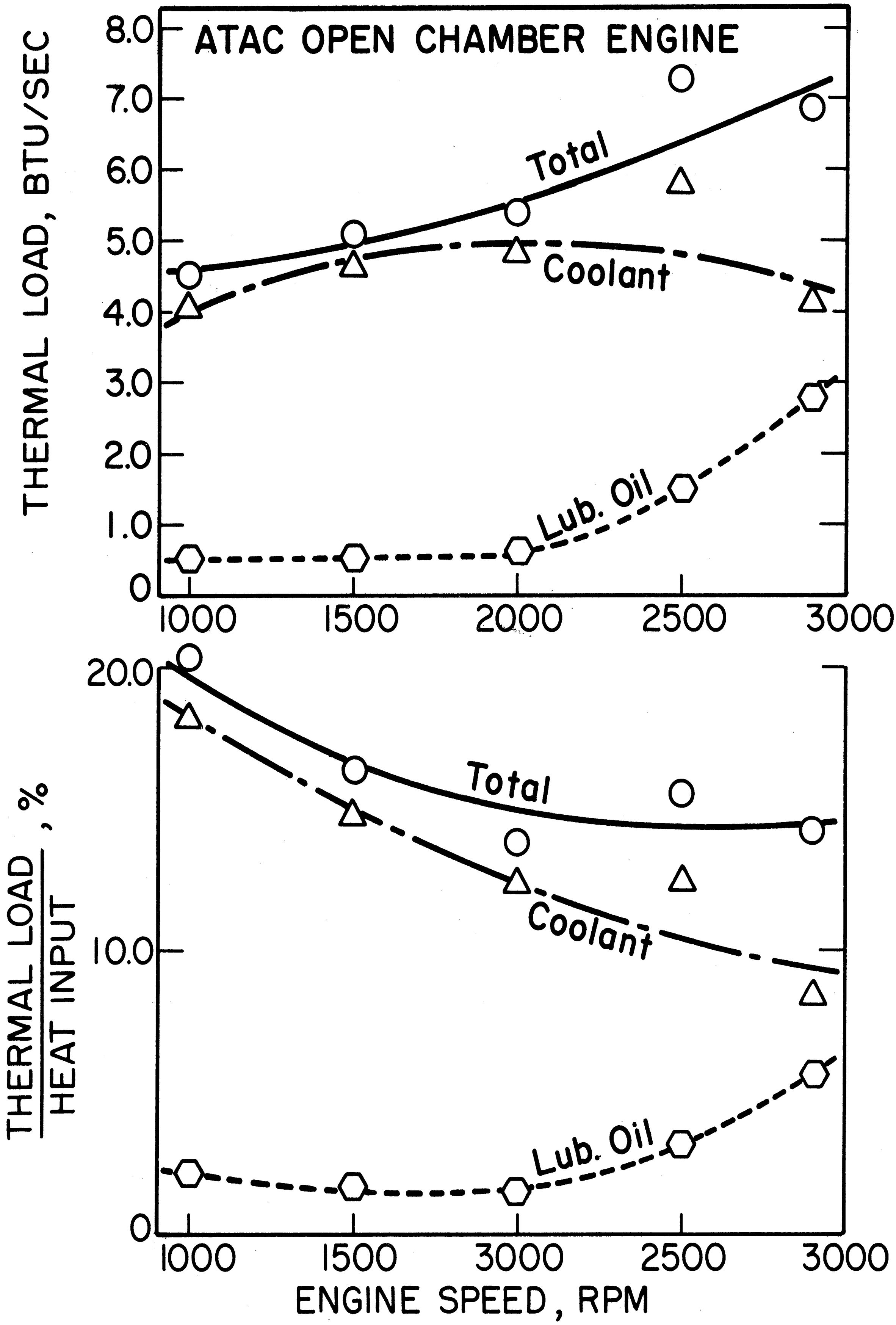


Fig. 18. Effect of engine speed on thermal loading.

IV. EFFECT OF COOLANT TEMPERATURE ON IGNITION DELAY AND OTHER COMBUSTION PHENOMENA

This series of tests was run to study the effect of coolant temperature on the combustion process in the ATAC engine, in an effort to evaluate the possibility of running coolant systems at temperatures higher than the present temperature levels of about 200°F. The increase in the coolant temperature results in an increase in the temperature differential between the coolant and air, and reduce the size of the radiator for a certain cooling load. At the present time, it seems that the radiator size might limit the increase in power output of diesel engines, specially in some military applications. In the present experimental study the thermal loading was measured, and the coolant used was "ethylene glycol."

The tests covered a range of coolant temperatures from 150°F to 300°F. The temperature of the lubricating oil in the crankcase was kept at a constant level of 200°F. This limitation was made to avoid any trouble that might occur due to the increase in the lubricating oil temperature.

Conditions of the Test

Fuel - CITE refree grade (Mil-F-45121)

Pressure in surge tanks = barometric

Inlet air temperature = 81°F

Fuel-air ratio = 0.0313

Injector opening pressure = 3000 psia

Injector timing (start of needle lift) = 21° B.T.D.C.

Lubricating oil temperature = 200°F

Engine speed = 2000 rpm

Variables

Outlet coolant temperature: 156°F-305°F

Results

The results for the effect of coolant temperature on the different combustion phenomena are given in Table 3 in Appendix B.

A. EFFECT OF COOLANT TEMPERATURE ON COMBUSTION PHENOMENA

The pressure rise delay did not change with the increase in coolant temperature. The average value for the ignition delay for seven runs was 0.681 s sec, the maximum ignition delay was 0.709; or 4% above the average. The minimum ignition delay was 0.667; or 2% below the average. These changes in ignition delays can be considered as random changes.

The experimental results showed no effect for the coolant temperature upon the compression pressure, maximum cycle pressure and rate of pressure rise. The exhaust gas temperature increased with the coolant temperature. At a coolant temperature of 156°F the exhaust temperature was 846°F, and increased to 950°F at coolant temperature of 305°F.

B. EFFECT OF COOLANT TEMPERATURE ON THERMAL LOAD

The thermal load can be considered to be composed of heat losses to the coolant, and heat losses to the lubricating oil. The variation in these heat losses with coolant temperatures in shown in Fig. 19. The increase in temperature from 156.6°F to 305°F reduced the total thermal loading from 30,600 Btu/hr to about 20,500 Btu/hr. This is mainly due to the reduction in the temperature difference between the gases and the walls. The corresponding thermal loading as a percentage of the power output is 1660 Btu/B.H.P. hr and 1240 Btu/H.P. hr respectively.

The percentage heat loss to the coolant, shown in Fig. 20, decreased from 15.3% at 156°F, to 8.4% at 305°F. For the lubricating oil the percentage heat losses increased from 2.4% at 156°F to 5.4% at 305°F. The percentage total heat losses to the coolant and the lubricating oil decreased from 17.7% at 156°F to 13.8% at 305°F.

C. EFFECT OF COOLANT TEMPERATURE ON INJECTION PROCESS

No effect was observed for the coolant temperature on injection timing, the period of main injection or the period of after injection. The only effect on the injection system was observed in the amount of after injection. The needle lift during after injection shown in Fig. 21 was observed to decrease with the increase in coolant temperature up to 230°F, after which it increased again. Figure 22 shows the needle lift diagrams at coolant temperatures of 217°F and 304.3°F. It is noticed that at the higher temperature the needle lift, was approximately twice as much as that at the lower temperature.

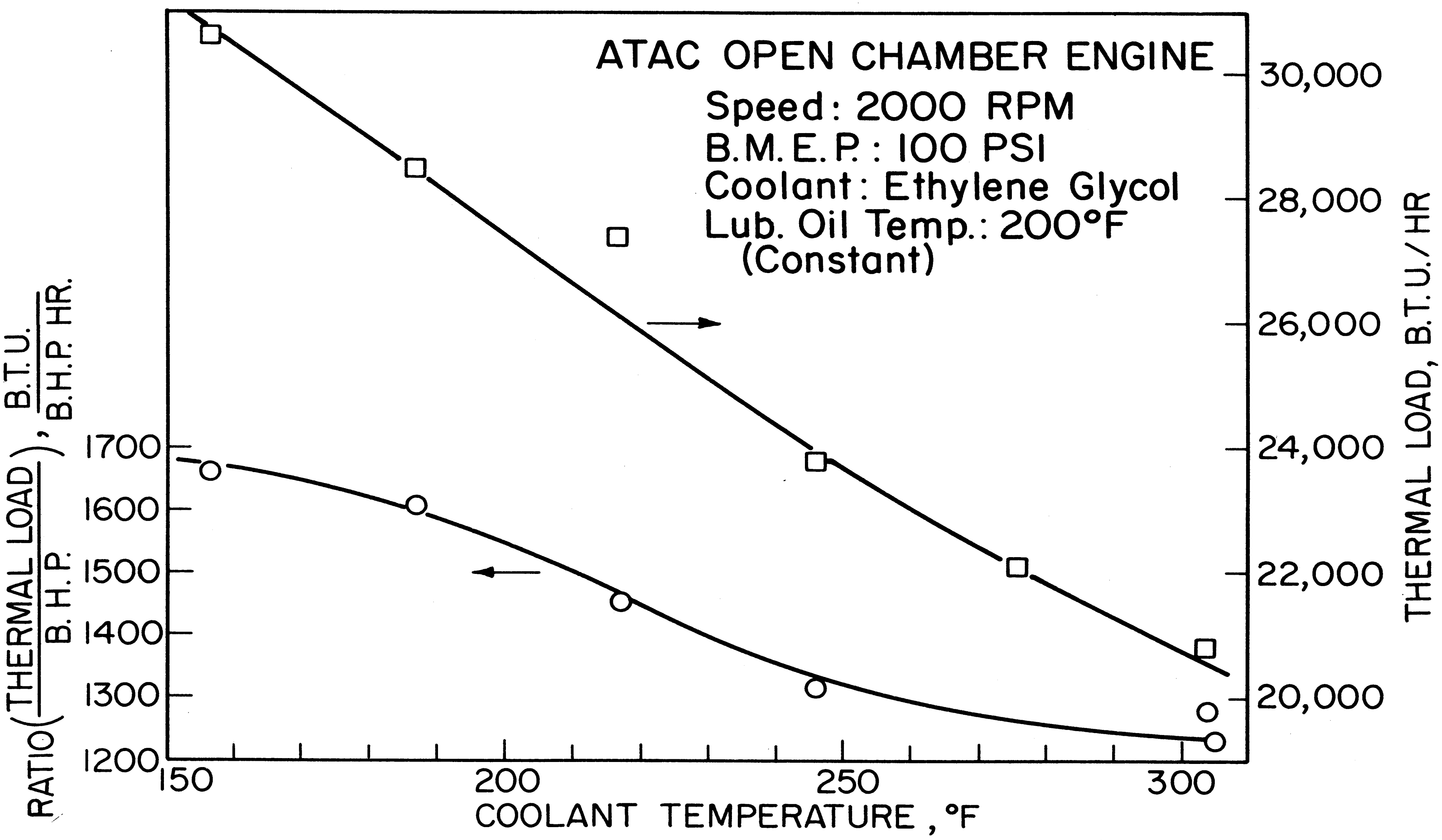


Fig. 19. Effect of coolant temperature on thermal loading.

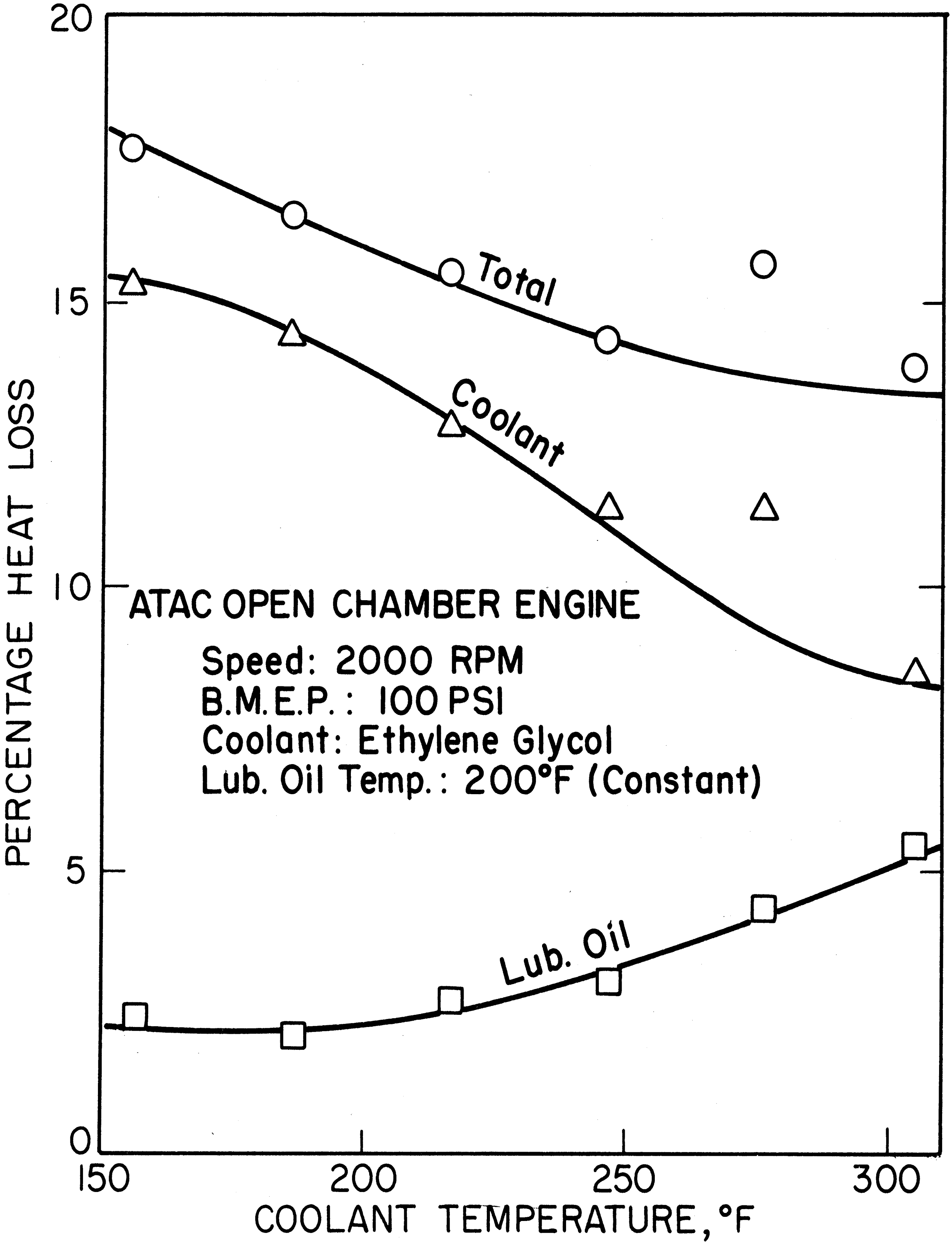


Fig. 20. Effect of coolant temperature on % heat lost to coolant and lubricating oil.

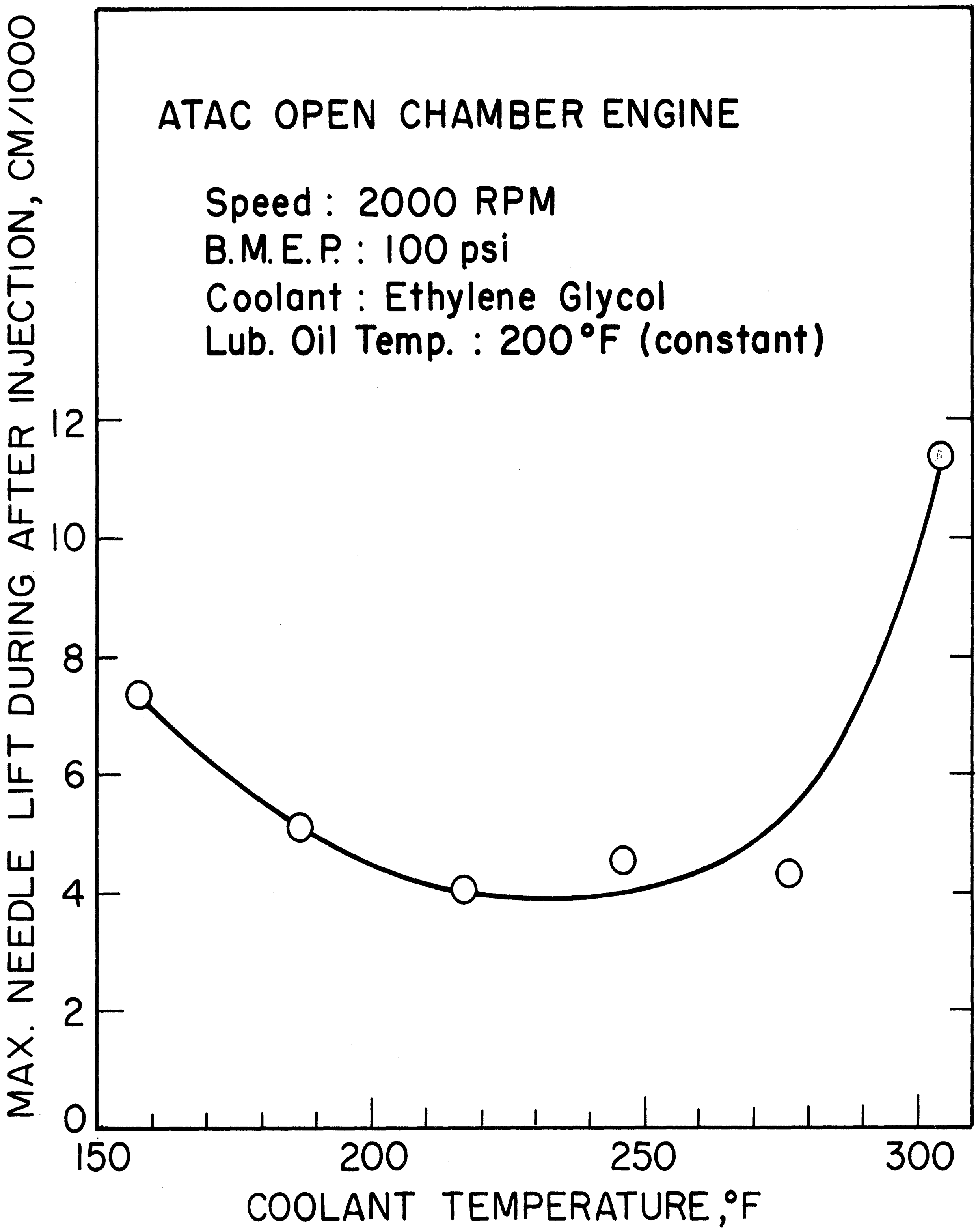
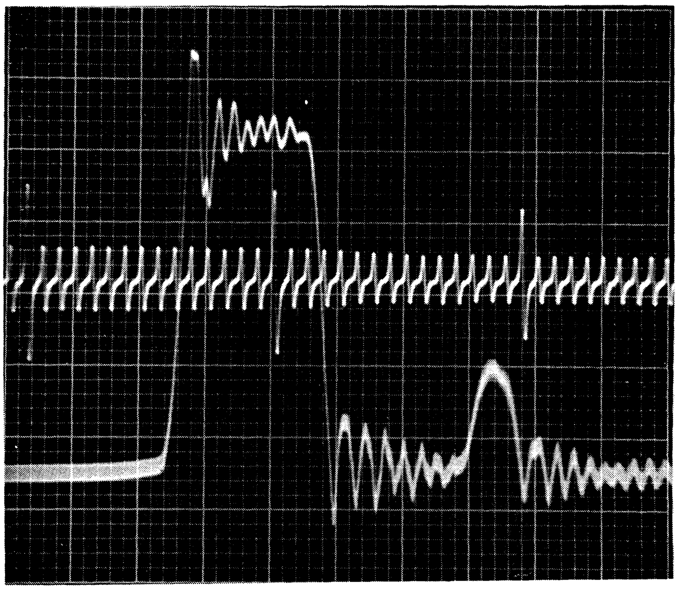
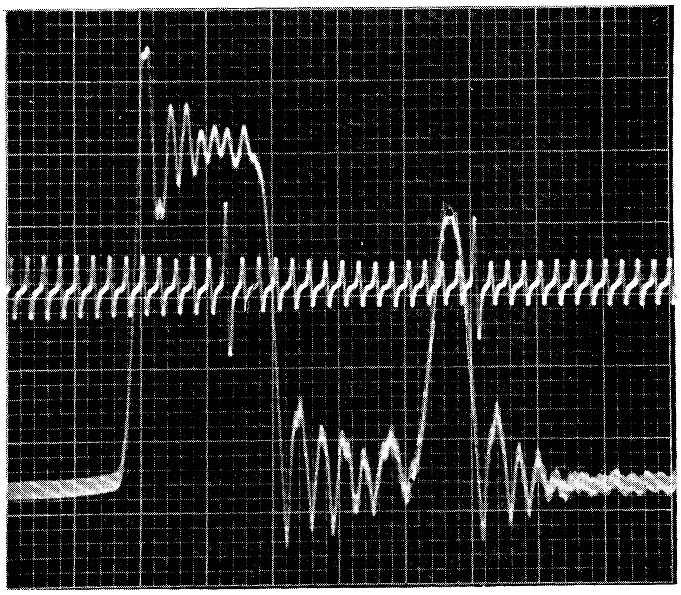


Fig. 21. Effect of coolant temperature on needle lift during after injection.



(a) Coolant temperature = 217°F



(b) Coolant temperature = 304.3°F

. 22. Needle lift diagrams with coolant temperatures of 217°F and 304.3°F.

V. PISTON AND LINER INSPECTION AFTER THE HIGH COOLANT TEMPERATURE TESTS

To check the condition of piston, liner and valve seats after the completion of the high coolant temperature tests, the cylinder head was removed. The liner, piston and valves were examined and found in a fair condition without any sign of overheating. The piston rings and valves were replaced with new ones. The new valves were lapped on the seats.

APPENDIX A

COMPUTER PROGRAMS

1. MAIN COMPUTER PROGRAMS

These computer programs are written in the Michigan Algorithm Decoder (MAD) language which is the language used at The University of Michigan Computing Center.

Program

1. Heat Release Calculations
2. Sequential Cycle Data Analysis
3. Engine Data Reading and Printing (ENGDAT)
4. Engine Data Calculations (ENGCAL)
5. Fuel Injection System Analysis
6. Equivalent Area of Injection as a Function of Injector-Needle Lift (AREAS)
7. Integration of Given Data (INTDER)
8. Best Straight Line to Fit a Group of Points (BLINE)
9. Curve Fitting (DB4T11)
10. Cylinder Volume and Gradient (CYLVOL, CYLGRA)
11. Cylinder Gas Properties (BBCFAC, BBRAN, BBFAR, BBLFT3)
12. Title Printing (TITLE)
13. Fuel Properties (FULHCR, FULDEN, FULFLO)
14. Coolant and Oil Properties (COLID, OILID, COLDEN, OILDEN, COLCP, OILCP, COLNU)
15. Calculation of the Integral Mean Value of Given Data (MEAN)
16. Interpolation (INTERP)

17. Air Flow Rate (AIRFLO)

18. Average Values and Errors (AVEERR)

19. Cylinder Wall Temperature from Millivolt Readings (THERMO)

20. Check on Missing Data (LACK)

21. Rounding of Numbers (IROUND)

2. DATA PLOTTING ROUTINES

Program

22. Axes Plotting (AXIS)

23. Curve Plotting (GRAPH)

24. Results Punching (PUNCH)

Computer Program 1

Title: Heat Release Calculations

Purpose: To calculate the net heat release from the combustion reactions over a range of crank angles starting from the point of injection to near the end of the combustion process.

Input:

1. Cylinder pressure obtained and punched from the program, "Sequencial Cycle Data Analysis"

2. Engine test data

Procedure:

1. Read cylinder pressure, from the program, "Sequencial Cycle Data Analysis", program 2.

2. Interpolate and determine the pressure every one-eighth of a crank-angle degree.

3. Calculate the mass of the charge in the cylinder by using the program "ENGCAL", program 4.

4. Calculate the average temperature of the gases from their pressure, volume, and mass, by using the "Beattie-Bridgeman" equation of state. The subroutine used for these calculations is given in program no. 11.

5. Calculate the rate of change of temperature ($dT/d\theta$), w.r.t. the crank angles, by using the program 9.

6. Calculate the volume gradient ($dV/d\theta$) by using the program 10.

7. Calculate the rate of doing work at any crank angle θ,

$$\frac{\delta w}{\delta \theta} = 1.07116 \times 10^{-4} \times \frac{dV}{d\theta}$$

where $dV/d\theta$ is the change in cylinder volume w.r.t. the crank angles.

8. Calculate the change of the internal energy, dU, by using the following equation:

$$\frac{dU}{d\theta} = M \times c_v \times \frac{dT}{d\theta}$$

where c_v is the specific heat at constant volume,

$$c_v = (7.864 - \frac{36.1}{\sqrt{T}} - \frac{2387}{T} + \frac{905000}{T^2})$$

9. Calculate the rate of heat release from

$$\frac{\delta Q}{\delta\theta} = \frac{dU}{d\theta} + \frac{\delta w}{\delta\theta}$$

where Q is heat transfer

List of Assisting Subroutines:

1. Program to calculate the mass of the charge and the fuel-air ratio (name: ENGCAL) program 4.

2. Program to calculate the hydrogen to carbon ratio of the fuel (name: FULHCR) program 13.

3. Program to round out numbers (name: I ROUND) program 21.

4. Program for interpolation (name: INTERP) program 16.

5. Program to calculate the temperature in degrees Rankine (name: BBRAN) program 11.

6. Program to calculate the temperature gradient (name: DB4T11) program 9.

7. Program to calculate the cylinder volume gradient (CYLGRA) program 10.

8. Program to punch the results (PUNCH) program 24.

9. Library ploting subroutines (PLTPAP., PLTMAX, PLTOFS., PLINE., PLTEND).

Computer Program 1

Heat Release Calculations

```
          D'N SPEC(18), ID(3), DATA(21), CALC(20),
         1      (DBTDC, CP, T, DW, DU, DT, STORE, DQ)(1024)
          I'R IROUND., NUMDAT, ENDDAT, NUMSEQ, ENDSEQ, I
AGAIN     ENGCAL.(1,SPEC,ID(1),DATA(1),CALC(1))
          GAS = CALC(5) + CALC(7)
          RGAS = (CALC(5)*.371110 + CALC(7)*(.371110 + CALC(4)/
         1          (.3757 + 4.4769/FULHCR.(SPEC(4))))/(1 + CALC(4)))/GAS
          DU = GAS/28.966
          GAS = GAS*1728.
          R'T $S15,F16.10,S5,F16.10,S7,F16.10*$, BEGIN, EVERY, END
          NUMDAT = 1 + IROUND.((END-BEGIN)/EVERY)
          ENDDAT = 1 + 8*NUMDAT
          NUMSEQ = ENDDAT - 8
          ENDSEQ = NUMSEQ + 1
          DELSEQ = EVERY/8.
          DBTDC = BEGIN - DELSEQ
          (I = 1, 1, I .E. ENDSEQ,
         1  DBTDC(I) = DBTDC + I*DELSEQ,
         2  DBTDC(I) = 0. + DBTDC(I))
          R'T $S10,10F7.3*$, (I = 1, 8, I .E. ENDDAT, CP(I))
          INTERP.(NUMDAT,DBTDC(1),8,CP(1))
          DW = 1./.3676/14.696/1728.
          T'H LOOP1, FOR I = 1, 1, I .E. ENDSEQ
          DBTDC = DBTDC(I)
          CP = CP(I)
          T = BBRAN.(CP,GAS/CYLVOL.(DBTDC),RGAS)
          T(I) = T
          DW(I) = 1.07116E-4*CP*CYLGRA.(DBTDC)
LOOP1     DU(I) = DU*(7.864 - 36.1/SQRT.(T) - 2387./T + 905000./T/T)
          DB4T11.(NUMSEQ,-DELSEQ,1,T(1),STORE(1),DT(1),
         1          STORE(1),STORE(1),STORE(1))
          T'H LOOP2, FOR I = 1, 1, I .E. ENDSEQ
          DU(I) = DU(I)*DT(I)
LOOP2     DQ(I) = DW(I) + DU(I)
          READ DATA
          P'T $(1H1/1H054(/F10.4,2F10.1,3P4F10.2))*$,
         1  (I = 1, 1, I .E. ENDSEQ,
         2  DBTDC(I), CP(I), T(I), DW(I), DU(I), DQ(I),
         3  DQ(I)*EXP.(SLOPE/T(I)))
          PUNCH.(ID(1),$DQ   $,1,NUMSEQ,1,DQ(1))
          PLTPAP.($400$)
          PLTXMX.(14.90)
          PLTOFS.(21.,-2.,-.2,.06666666667,.65,.41)
          PLINE.(DBTDC(1),DQ(1),NUMSEQ,1,0,0,1.)
          PLTEND.
          T'O AGAIN
          E'M
```

Computer Program 2

Title: Sequencial Cycle Data Analysis

Purpose: To determine the cylinder pressure during the cycle from the time of inlet valve closing to the exhaust valve opening.

Input: Data points measured from a group of traces taken for different intervals during the cycle from the inlet valve closing to exhaust valve opening.

Procedure:

1. Read a sequence of data points as indicated under "Input".

2. Statistically adjust the data giving adjusted values, errors, deviations, and probabilities.

3. Curve fit the adjusted values by applying a fourth degree polynomial curve through eleven consecutive points. The program for this step is known as DB4T11 program.

4. Print, punch or plot the results.

List of Assisting Subroutines:

1. Program to print the title (name: TITLE) program 12.

2. Program to curve fit the adjusted values (name: DB4T11) program 9.

3. Program to use the program in (2), for the required number of times and for interpolation (USEDB4, INTERP) program 16.

4. Program to calculate cylinder well temperature from milivolt readings of traces (THERMO) program 19.

5. Punching, plotting and graphing programs (PLOT, GRAPH, PUNCH) program 23 and 24.

NOTE: This program was used to calculate cylinder gas pressure as shown in Fig. 6.

Computer Program 2

Sequential Cycle Data Analysis

```
        D'N CM(1689), (DBTDC, DATA, BEST)(1441), (COMMON, ERRCOM)
        1     (498), (MVCM, CMREF, ERRREF, UNITCM, BTDC, REF, REFERR,
        2     BLO, BLOERR, ADJ, ADJERR)(250), SPEC(19), YTITLE(17),
        3     HEAD(16), VALUES(7), SCALES(5), NUMBER(3)
        EQUIVALENCE (DBTDC, UNITCM), (BEST, REFERR),
        1     (BEST(251), BLO), (BEST(502), BLOERR), (BEST(753), ADJ),
        2     (BEST(1004), ADJERR)
        I'R TITLE., LINE, NUMBER, P, COMMON, BGN, END, LAST, OBS, FV,
        1     I, J, LINES, SPEC, NUMDAT, YTITLE, HEAD, IROUND., DEL,
        2     BCDBN.
        B'N EXACT, DOPLOT, DOGRPH, DOREAD, DOPRNT, DOPNCH, DOTELL,
        1     DIDDB4, WT
        F'E FV
NXTSET  LINE = TITLE.(1,SPEC)
        READ DATA
        SPACE.(LINE,6,24)
        P'T $10H-DATA SET C4,9H;  RUN # C4,15H;  RESULTS SET C4,4H HA
        1SI4,23H PHOTOS (SCALE FACTOR =F11.6,30H UNITS/MV);  DATA TAKE
        2N @ EACHF8.2,6H DBTDC*$,
        3  SPEC...SPEC(2), NUMBER, VALUES, VALUES(2)
        UNITCM(1) = VALUES*MVCM(1)
        ZERO.(COMMON,END,REF(1),BLO(1))
        BTDC(1) = VALUES(1)
        REFERR = UNITCM(1)*ERRREF(1)
        REFERR(1) = REFERR*REFERR
        BLOERR(1) = REFERR(1)
        T'H PHOTOS, FOR P = 2, 1, P .G. NUMBER
        UNITCM = VALUES*MVCM(P)
        UNITCM(P) = UNITCM
        COMMON = COMMON + 1
        BGN = COMMON(COMMON)
        W'R BGN .NE. END + 1, ERROR.
        BGNERR = UNITCM*ERRCOM(COMMON)
        COMMON = COMMON + 1
        END = COMMON(COMMON)
        ENDERR = UNITCM*ERRCOM(COMMON)
        LAST = P - 1
        BTDC(P) = BTDC(LAST) + (END - BGN)*VALUES(2)
        REF(P) = UNITCM(1)*(CMREF(P) - CMREF(1))
        REFERR = UNITCM(1)*ERRREF(P)
        REFERR(P) = REFERR*REFERR
        BLO(P) = BLO(LAST) + UNITCM*(CM(END) - CM(BGN))
PHOTOS  BLOERR(P) = BLOERR(LAST) + ENDERR*ENDERR + BGNERR*BGNERR
        T'H ADJUST, FOR P = 1, 1, P .G. NUMBER
        EXACT = 0B
        ADJ = 0.
        ADJERR = 0.
        T'H OBSERV, FOR OBS = 1, 1, OBS .G. NUMBER
        NUMER = REF(OBS) + BLO(P) - BLO(OBS)
        DENOM = REFERR(OBS) + .ABS. (BLOERR(P) - BLOERR(OBS))
        W'R DENOM .E. 0.
        W'R EXACT
        W'R .ABS. ((ADJ - NUMER)/UNITCM(P)) .G. .005, ERROR.
        O'E
        EXACT = 1B
        ADJ = NUMER
        ADJ(P) = NUMER
        ADJERR(P) = 0.
        E'L
```

```
               O'R .NOT. EXACT
               ADJ = ADJ + NUMER/DENOM
               ADJERR = ADJERR + 1./DENOM
               E'L
               C'E
               W'R .NOT. EXACT
               ADJ(P) = ADJ/ADJERR
               ADJERR(P) = 1./ADJERR
               E'L
ADJUST         C'E
               P'T TOP
               V'S TOP = $132H0|--SEQUENTIAL PHOTO ANALYSIS DATA (#1 = REFER
               1ENCE FOR SEQUENTIAL BLOWUPS)--|     PERCENT      ·REFERENCE
               2  BLOWUPS       ADJUSTMENTS/104H PHO   MV/CM   DBTDC ON 1 ERR SEQ
               3UENTIAL CENTIMETER MEASUREMENTS ON THE BLOWUPS PROBAB FACTOR
               4 UNITS    ERR2(14H    UNITS    ERR)*$
               P'T  4H    1F9.3*$, MVCM(1)
               P = 1
               EV = 5 - NUMBER(1)
               POINT.
               LINE = LINE + 8
               COMMON = 0
               I = 1
               J = 1
               DATA(1) = ADJ(1)
               T'H PRINT, FOR P = 2, 1, P .G. NUMBER
               COMMON = COMMON + 1
               BGN = COMMON(COMMON)
               BGNERR = ERRCOM(COMMON)
               COMMON = COMMON + 1
               END = COMMON(COMMON)
               LINES = 4 + (END - BGN)/10
               LINE = LINE + LINES
               W'R LINE .G. 60
               P'T $1H1/1H-/1H0*$
               P'T TOP
               LINE = 12 + LINES
               E'L
               LAST = P - 1
               ADJ = ADJ(P) - ADJ(LAST)
               BLO = BLO(P) - BLO(LAST)
               FACTOR = ADJ/BLO
               UNITCM = FACTOR*UNITCM(P)
               DATA = ADJ(LAST) - UNITCM*CM(BGN)
               (I = I + 1, 1, I .G. END,
               1  J = J + NUMBER(3),
               2  DATA(J) = DATA + UNITCM*CM(I))
               P'T $F27.2/I4,F9.3,S65,F6.2,F8.3*$,
               1  BGNERR, P, MVCM(P),
               2  100.*(1. - ERF.(.ABS.(BLO - ADJ)/SQRT.(2.*(
               3  BLOERR(P) - BLOERR(LAST) + ADJERR(P) + ADJERR(LAST))))),
               4  100.*(FACTOR - 1.)
               W'R LINES .E. 4
               P'T $1H+S26,10F5.2*$, CM(BGN)...CM(END)
               O'E
               P'T $1H+S26,10F5.2/(S27,10F5.2)*$, CM(BGN)...CM(END)
               E'L
               P'T $F27.2*$, ERRCOM(COMMON)
PRINT          POINT.
               DOPLOT = SPEC(3) .E. $PLOT$
```

Computer Program 2

Sequential Cycle Data Analysis

```
         D'N CM(1689), (DBTDC, DATA, BEST)(1441), (COMMON, ERRCOM)
        1    (498), (MVCM, CMREF, ERRREF, UNITCM, BTDC, REF, REFERR,
        2    BLO, BLOERR, ADJ, ADJERR)(250), SPEC(19), YTITLE(17),
        3    HEAD(16), VALUES(7), SCALES(5), NUMBER(3)
         EQUIVALENCE (DBTDC, UNITCM), (BEST, REFERR),
        1    (BEST(251), BLO), (BEST(502), BLOERR), (BEST(753), ADJ),
        2    (BEST(1004), ADJERR)
         I'R TITLE., LINE, NUMBER, P, COMMON, BGN, END, LAST, OBS, FV,
        1    I, J, LINES, SPEC, NUMDAT, YTITLE, HEAD, IROUND., DEL,
        2    BCDBN.
         B'N EXACT, DOPLOT, DOGRPH, DOREAD, DOPRNT, DOPNCH, DOTELL,
        1    DIDDB4, WT
         F'E FV
NXTSET   LINE = TITLE.(1,SPEC)
         READ DATA
         SPACE.(LINE,6,24)
         P'T $10H-DATA SET C4,9H:  RUN # C4,15H:  RESULTS SET C4,4H HA
        1SI4,23H PHOTOS (SCALE FACTOR =F11.6,30H UNITS/MV);  DATA TAKE
        2N @ EACHF8.2,6H DBTDC*$,
        3  SPEC...SPEC(2), NUMBER, VALUES, VALUES(2)
         UNITCM(1) = VALUES*MVCM(1)
         ZERO.(COMMON,END,REF(1),BLO(1))
         BTDC(1) = VALUES(1)
         REFERR = UNITCM(1)*ERRREF(1)
         REFERR(1) = REFERR*REFERR
         BLOERR(1) = REFERR(1)
         T'H PHOTOS, FOR P = 2, 1, P .G. NUMBER
         UNITCM = VALUES*MVCM(P)
         UNITCM(P) = UNITCM
         COMMON = COMMON + 1
         BGN = COMMON(COMMON)
         W'R BGN .NE. END + 1, ERROR.
         BGNERR = UNITCM*ERRCOM(COMMON)
         COMMON = COMMON + 1
         END = COMMON(COMMON)
         ENDERR = UNITCM*ERRCOM(COMMON)
         LAST = P - 1
         BTDC(P) = BTDC(LAST) + (END - BGN)*VALUES(2)
         REF(P) = UNITCM(1)*(CMREF(P) - CMREF(1))
         REFERR = UNITCM(1)*ERRREF(P)
         REFERR(P) = REFERR*REFERR
         BLO(P) = BLO(LAST) + UNITCM*(CM(END) - CM(BGN))
PHOTOS   BLOERR(P) = BLOERR(LAST) + ENDERR*ENDERR + BGNERR*BGNERR
         T'H ADJUST, FOR P = 1, 1, P .G. NUMBER
         EXACT = 0B
         ADJ = 0.
         ADJERR = 0.
         T'H OBSERV, FOR OBS = 1, 1, OBS .G. NUMBER
         NUMER = REF(OBS) + BLO(P) - BLO(OBS)
         DENOM = REFERR(OBS) + .ABS. (BLOERR(P) - BLOERR(OBS))
         W'R DENOM .E. 0.
         W'R EXACT
         W'R .ABS. ((ADJ - NUMER)/UNITCM(P)) .G. .005, ERROR.
         O'E
         EXACT = 1B
         ADJ = NUMER
         ADJ(P) = NUMER
         ADJERR(P) = 0.
         E'L
```

Computer Program 2 (Continued)

```
          O'R .NOT. EXACT
          ADJ = ADJ + NUMER/DENOM
          ADJERR = ADJERR + 1./DENOM
          E'L
          C'E
          W'R .NOT. EXACT
          ADJ(P) = ADJ/ADJERR
          ADJERR(P) = 1./ADJERR
          E'L
ADJUST    C'E
          P'T TOP
          V'S TOP = $132H0|--SEQUENTIAL PHOTO ANALYSIS DATA (#1 = REFER
         1ENCE FOR SEQUENTIAL BLOWUPS)--|     PERCENT      REFERENCE
         2 BLOWUPS      ADJUSTMENTS/104H PHO  MV/CM  DBTDC ON 1 ERR SEQ
         3UENTIAL CENTIMETER MEASUREMENTS ON THE BLOWUPS PROBAB FACTOR
         4 UNITS   ERR2(14H    UNITS    ERR)*$
          P'T  4H   1F9.3*$, MVCM(1)
          P = 1
          FV = 5 - NUMBER(1)
          POINT.
          LINE = LINE + 8
          COMMON = 0
          I = 1
          J = 1
          DATA(1) = ADJ(1)
          T'H PRINT, FOR P = 2, 1, P .G. NUMBER
          COMMON = COMMON + 1
          BGN = COMMON(COMMON)
          BGNERR = ERRCOM(COMMON)
          COMMON = COMMON + 1
          END = COMMON(COMMON)
          LINES = 4 + (END - BGN)/10
          LINE = LINE + LINES
          W'R LINE .G. 60
          P'T $1H1/1H-/1H0*$
          P'T TOP
          LINE = 12 + LINES
          E'L
          LAST = P - 1
          ADJ = ADJ(P) - ADJ(LAST)
          BLO = BLO(P) - BLO(LAST)
          FACTOR = ADJ/BLO
          UNITCM = FACTOR*UNITCM(P)
          DATA = ADJ(LAST) - UNITCM*CM(BGN)
          (I = I + 1, 1, I .G. END,
         1  J = J + NUMBER(3),
         2  DATA(J) = DATA + UNITCM*CM(I))
          P'T $F27.2/I4,F9.3,S65,F6.2,F8.3*$,
         1  BGNERR, P, MVCM(P),
         2  100.*(1. - ERF.(.ABS.(BLO - ADJ)/SQRT.(2.*(
         3  BLOERR(P) - BLOERR(LAST) + ADJERR(P) + ADJERR(LAST))))),
         4  100.*(FACTOR - 1.)
          W'R LINES .E. 4
          P'T $1H+S26,10F5.2*$, CM(BGN)...CM(END)
          O'E
          P'T $1H+S26,10F5.2/(S27,10F5.2)*$, CM(BGN)...CM(END)
          E'L
          P'T $F27.2*$, ERRCOM(COMMON)
PRINT     POINT.
          DOPLOT = SPEC(3) .E. $PLOT$
```

```
         DOGRPH = SPEC(4) .E. $GRPH$
         DOREAD = DOGRPH .OR. DOPLOT
         DOPRNT = SPEC(5) .E. $PRNT$
         DOPNCH = SPEC(6) .E. $PNCH$
         DOTELL = DOPNCH .OR. DOPRNT
         W'R DOTELL .OR. DOREAD
         DELINT = VALUES(2)/NUMBER(3)
         P'T $26H-DATA WILL BE CURVE FITTEDI2,23H TIMES, SHIFTED SO TH
        1ATF8.2,10H DBTDC HASF10.4,20H UNITS, INTERPOLATEDI3,11H TO 1
        2(EACHF12.6,7H DBTDC)*$,
        3  NUMBER(2), VALUES(3), VALUES(4), NUMBER(3), DELINT
         NUMDAT = 1 + (J - 1)/NUMBER(3)
         DBTDC(1) = BTDC(1)
         DBTDC = BTDC(1) - DELINT
         (I = 1, 1, I .G. J,
        1  DBTDC(I) = DBTDC + I*DELINT)
         USEDB4.(NUMDAT,VALUES(2),NUMBER(3),DATA(1),BEST(1),
        1        NUMBER(2),NODB4)
         DIDDB4 = 1B
         TERM = VALUES(4) - TAB.(VALUES(3),DBTDC(1),BEST(1),NUMBER(3),
        1                       NUMBER(3),5,NUMDAT,1.)
         T'O SKIP
NODB4    DIDDB4 = 0B
         TERM = VALUES(4) - TAB.(VALUES(3),DBTDC(1),DATA(1),NUMBER(3),
        1                       NUMBER(3),5,NUMDAT,1.)
SKIP     WT = SPEC(2) .RS. 24 .E. $000QWT$
         W'R TERM .NE. 0.
         W'R DOGRPH
         T'H SHIFTR, FOR P = 1, 1, P .G. NUMBER
         REF(P) = REF(P) + TERM
SHIFTR   W'R WT, REF(P) = THERMO.(REF(P))
         E'L
         T'H SHIFTD, FOR I = 1, NUMBER(3), I .G. J
         DATA(I) = DATA(I) + TERM
         W'R DIDDB4, BEST(I) = BEST(I) + TERM
         W'R WT
         DATA(I) = THERMO.(DATA(I))
         W'R DIDDB4, BEST(I) = THERMO.(BEST(I))
SHIFTD   E'L
         E'L
         INTERP.(NUMDAT,DBTDC(1),NUMBER(3),DATA(1))
         W'R DIDDB4, INTERP.(NUMDAT,DBTDC(1),NUMBER(3),BEST(1))
         W'R DOREAD
         XTITLE = $F4$
         XTITLE(1) = 23
         V'S XTITLE(2) = $CRANKANGLE DEGREES BTDC$
         READ DATA
         W'R DOPLOT
         W'R DIDDB4
         PLOT.(SCALES,XTITLE,YTITLE,HEAD,J,DBTDC(1),BEST(1))
         O'E
         PLOT.(SCALES,XTITLE,YTITLE,HEAD,J,DBTDC(1),DATA(1))
         E'L
         E'L
         W'R DOGRPH
         GRAPH.(SCALES,XTITLE,YTITLE,HEAD)
         PLINE.(BTDC(1),REF(1),NUMBER,1,-1,1,1.)
         I = 1. + .06*.ABS.(SCALES(1)/SCALES(2)/DELINT)
         J = 1 + (J - 1)/I
         PLINE.(DBTDC(1),DATA(1),J,I,0,0,1.)
```

Computer Program 2 (Concluded)

```
      W'R DIDDB4, PDSHLN.(DBTDC(1),BEST(1),J,I,.05,1.)
      PLTEND.
      E'L
      E'L
      W'R DOTELL
      W'R DIDDB4
      TELL.(BEST)
      O'E
      TELL.(DATA)
      E'L
      E'L
      E'L
      T'O NXTSET
      I'N POINT.
      P'T $F18.2,F5.2,F4.2,S51,F6.2,S6,3(F8.'FV',F6.'FV')*$,
     1 BTDC(P), CMREF(P), ERRREF(P), 100.*(1. - ERF.(.ABS.
     2 (REF(P) - ADJ(P))/SQRT.(2.*(REFERR(P) + ADJERR(P))))),
     3 REF(P), SQRT.(REFERR(P)), BLO(P), SQRT.(BLOERR(P)),
     4 ADJ(P), SQRT.(ADJERR(P))
      E'N
      E'N
      I'N TELL.(DAT)
      BGN = 1 + IROUND.((VALUES(5) - VALUES(1))/DELINT)
      DEL = IROUND.(VALUES(6)/DELINT)
      NUMDAT = 1 + IROUND.((VALUES(7) - VALUES(5))/DELINT)/DEL
      END = BGN + NUMDAT*DEL
      FV = FV + 2
      W'R WT, FV = FV - 1
      W'R DOPRNT, P'T $1H1/1H-5(F13.'FV',2H =F10.4,1H,)/(S1,5(F13.'
     1FV',2H =F10.4,1H,))*$,
     2 (I = BGN, DEL, I .E. END, DAT(I), DBTDC(I))
      W'R DOPNCH
      SPEC(1) = BCDBN.(SPEC(1))
      PUNCH FORMAT $I4,S2,C4,5HBGN =F16.10,5H, FORF16.10,7H, END =F
     116.10,5H BTDC*$, SPEC(1), SPEC(2), DBTDC(BGN),
     2 DBTDC(DEL) - DBTDC, DBTDC(END - DEL)
      PUNCH.(SPEC(1),SPEC(2),7-FV,NUMDAT,DEL,DAT(BGN))
      E'L
      E'N
      E'N
      E'M
```

Computer Program 3

Title: Engine Data Reading and Printing

Purpose: To read engine data and specifications, calculate the mean values and root mean square errors, and tabulate the experimental observations.

Input:

A. Engine Specifications and Conditions of Test

1. Runs identification
2. Fuel used
3. Injector opening pressure
4. Oil used
5. Coolant used
6. Fuel consumption weight
7. Air flowmeter orifice

B. Engine Data

1. Engine speed in rpm
2. Load in lbs
3. Fuel consumption time in minutes
4. Fuel leakage past injector needle in liters per hour
5. Air pressure before air flowmeter orifice, in psia
6. Air temperature before air flowmeter orifice, in °F
7. Blowby rate, in ft^3/min
8. Barometric pressure, in in. Hg
9. Air surge tank gauge pressure, in. Hg

10. Cylinder pressure at the time of I.V. closing above the air surge tank pressure, in psi

11. Cylinder pressure at the point of injection above the cylinder pressure at I.V. closing, in psi

12. Cylinder pressure at the end of ignition delay, $I.D._p$ above the pressure at start of injection, in psi

13. Crank angle at the start of needle lift, in degrees

14. Crank angle at the end of ignition delay, in degrees

15. Crank angle at the start of illumination, in degrees

16. Inlet air temperature, degrees Fahrenheit

17. Minimum surface temperature of the combustion chamber wall, in millivolts

18. Surface temperature swing due to combustion, in millivolts

19. Exhaust gas temperature, in degrees Fahrenheit

20. Smoke meter reading, in Hartridge units

21. Oil temperatures at inlet and outlet of the oil cooler, in degrees Fahrenheit

22. Oil flowmeter reading, in cycles per sec

23. Coolant temperature at inlet and outlet from engine, in degree Fahrenheit

24. Pressure drop across the sharp edge orifice of the coolant flowmeter, in in. Hg

Procedure:

1. Read and print the engine specifications, conditions of runs, and data, in tabulated form.

List of Assisting Programs:

1. Program to print a title (TITLE) program 12.

2. Program to calculate the averages and errors (AVERMS) program 18.

NOTE: Items 10, 11, 12, 13, 14, 15, 17, 18 are obtained from the different oscilloscope traces photographed for the cycle.

Computer Program 3

Engine Data Reading and Printing (ENGDAT)

```
       EXTERNAL FUNCTION ENGDAT.(USING,SPEC,ID,DATA)
       I'R TITLE., LINE, BCDBN., N, SPEC, MAX, USING, USE, USE2,
      1    USE3, USE20, END20, END26, R, S, ID, END, BGN
       B'N MORE, LACK.
       LINE = TITLE.(1,SPEC)
       N = BCDBN.(SPEC(1))
       SPEC(1) = N
       MORE = N .G. 1
       W'R MORE
       MAX = N + 2
       O'E
       MAX = 1
       E'L
       USE = USING
       W'R N .L. 1 .OR. MAX .G. USE
NOGOOD ERROR RETURN
       E'L
       USE2 = USE + USE
       USE3 = USE2 + USE
       USE20 = 20*USE
       END20 = USE20 - 1
       END26 = 26*USE - 1
       R'T $I4,2C1,F5,F4.1,F3.2,F2.2,F3.1,F2,2F2.1,F4.1,F3.1,F4,F3,3
      1F4.1,F3,F3.1,F3.2,F4,F2/I4,F4.1,F3.1,F3,F4.1,2F3.1*$,
      2  (R = 0, 1, R .E. N, ID(R), ID(USE+R), ID(USE2+R),
      3  (S = R, USE, S .G. END20, DATA(S)),
      4  ID(USE3+R), (S = S, USE, S .G. END26, DATA(S)))
       T'H CHANGE, FOR R = 0, 1, R .E. N
       S = USE3 + R
       W'R ID(S) .NE. ID(R), T'O NOGOOD
       S = S + USE2
       TORF = DATA(S)
       W'R .NOT. LACK.(TORF) .AND. TORF .L. 40.,
      1    DATA(S) = 100. + TORF
       S = S + USE2
       PBAR = DATA(S)
       W'R .NOT. LACK.(PBAR)
       W'R PBAR .G. 2.
       PBAR = 20. + PBAR
       O'E
       PBAR = 30. + PBAR
       E'L
       DATA(S) = PBAR
CHANGE E'L
       W'R MORE
       T'H COLMNS, FOR S = 0, USE, S .G. END26
COLMNS AVEERR.(N,DATA(S))
       E'L
MORE1  BGNEND.(LINE,6,MAX,BGN,END,DONE1)
       W'R END .G. N, END = N
       P'T $10H-DATA SET C4,4H HASI5,12H RUNS.  THE C4,9H ENGINE (C4
      1,14H SLEEVE, IVC @C4,13H DBTDC) USED C4,7H FUEL (C4,7H PSI),
      2C4,10H OIL, AND C4,9H COOLANT.*$, SPEC...SPEC(8)
       P'T $114H0 FOR USE     SPEED LOAD    FUEL        AIR  BLOW  ROOM
      1-SURGE-@IVC-@INJ-RIS  DBTDC AT START OF  AIR MILLVOLTS EXHAUS
      2T/114H  RUN W O       RPM    LBS MIN L/HR  PSIG  F CFPM  INHG  I
      3NHG  PSI  PSI PSI   LIFT  RISE ILLUM   F   MIN  INC   F  HU/(
      4I5,2(S1,C1),F8,F6.1,F5.2,F4.2,F6.1,F4,F4.1,2F6.1,F5.1,F5,F4,F
      57.1,2F6.1,F5,F5.1,F5.2,F5,F3)*$,
      6  (R = BGN, 1, R .E. END, ID(R), ID(USE+R), ID(USE2+R),
```

```
          7  (S = R, USE, S .G. END20, DATA(S)))
           T'O MORE1
DONE1      W'R MORE, P'T $5H MEANF12,F6.1,F5.2,F4.2,F6.1,F4,F4.1,2F6.1,F
          15.1,F5,F4,F7.1,2F6.1,F5,F5.1,F5.2,F5,F3/5H ERRSF12,F6.1,F5.2,
          2F4.2,F6.1,F4,F4.1,2F6.1,F5.1,F5,F4,F7.1,2F6.1,F5,F5.1,F5.2,F5
          3,F3*$, (R = N, 1, R .E. MAX,
          4  (S = R, USE, S .G. END20, DATA(S)))
MORE2      BGNEND.(LINE,4,MAX,BGN,END,DONE2)
           W'R END .G. N, END = N
           P'T $37H- FOR  CRANKCASE OILS  COOLANT SYSTEM/38H  RUN  OUT(F
          1)INC  CPS  OUT(F)INC  INHG/(I5,F7.1,F5.1,F4,F7.1,2F5.1)*$,
          2  (R = BGN, 1, R .E. END, ID(R),
          3  (S = USE20+R, USE, S .G. END26, DATA(S)))
           T'O MORE2
DONE2      W'R MORE, P'T $5H MEANF7.1,F5.1,F4,F7.1,2F5.1/5H ERRSF7.1,F5.
          11,F4,F7.1,2F5.1*$, (R = N, 1, R .E. MAX,
          2  (S = USE20+R, USE, S .G. END26, DATA(S)))
           F'N LINE
           E'N
```

Computer Program 4

Title: Engine Data Calculations

Purpose: To calculate the different parameters of interest in the study of the combustion process.

Input: Same as ENGDAT (engine testing data and specifications) see ENGDAT input.

Procedure:

The following calculations, together with their mean values and root mean square curves are calculated.

1. Brake horsepower
2. Brake mean effective pressure, in psi
3. Brake specific fuel consumption in lb/hp/hr
4. Fuel-air ratio
5. Inlet air/cycle in lbm/cycle
6. Air blowby per cycle in lbm/cycle
7. Residual exhaust gas in lbm/cycle
8. Surge tank pressure in psia
9. Volumetric efficiency in %
10. Temperature at inlet valve close in degrees Farenheit
11. Average index of compression from inlet valve close to beginning of injection
12. Pressure at start of injection, psia
13. Density at start of injection, lbsm/ft^3
14. Temperature at start of injection, degrees Rankine
15. Average index of compression during delay

16. Average pressure during delay, psia

17. Average density during delay, lbm/ft^3

18. Average temperature during delay, degrees Rankine

19. Pressure rise delay in Msecs

20. Illumination delay in Msecs

21. Minimum cylinder wall temperature in degrees Farenheit

22. Maximum temperature swing during combustion in degrees Farenheit

23. Lubricating oil flow rate in gallons/min

24. Rate of heat loss to oil in Btu/sec

25. Percent of heat loss to oil

26. Coolant flow rate in gallons/min

27. Rate of heat loss to coolant in Btu/sec

28. Percent of heat loss to coolant

List of Assisting Programs:

1. Program DB4T11 (9)
2. Program CYLVOL, CYLGRA (10)
3. Program BBRAN, BBLFT3, BBFAR (11)
4. Program ENGDAT (3)
5. Program INTDER (7)
6. Program TITLE (12)
7. Program FULHCR, FULDEN, FULFLO (13)
8. Program 14 (coolant and oil properties)
9. Program MEAN (15)
10. Program AIRFLO (17)

11. Program AVEERR (18)

12. Program THERMO (19)

13. Program LACK (20)

Computer Program 4

Engine Data Calculations (ENGCAL)

```
      EXTERNAL FUNCTION ENGCAL.(USING,SPEC,ID,DATA,CALC)
      D'N STORE(54), (DAT, CAL)(28), (P, D, T)(10)
      I'R ENGDAT., LINE, SPEC, N, MAX, USING, USE, USE22, END22,
     1   END28, E, BCDBN., R, S, I, ID, RUN, END, BGN
      B'N MORE, LACK., LACK2., LACK3., LACK4.
      LINE = ENGDAT.(USING,SPEC,ID,DATA)
      N = SPEC(1)
      MORE = N .G. 1
      W'R MORE
      MAX = N + 2
      O'E
      MAX = 1
      E'L
      USE = USING
      USE22 = 22*USE
      END22 = USE22 - 1
      END28 = 28*USE - 1
      V'S DYNAM = 3000., 3571.
      V'S BMEP = 3.689, 3.187
      V'S EFF = 2414.38, 2483.42
      W'R SPEC(2) .E. $ATAC$
      E = 0
      O'E
      E = 1
      E'L
      RATIO = COMRAT.(VCLEAR,SPEC(2),SPEC(3))
      CLEAR = VCLEAR/1728.
      IVC = BCDBN.(SPEC(4))
      IVC = - 0. + IVC
      VIVC = CYLVOL.(IVC)
      DEN60 = FULPRO.(SPEC(5),HTOC,HETVAL)
      RVAPOR = 1./(17.908 + 1.503*HTOC)
      KEXH = .3757 + 4.4769/HTOC
      OILID.(HAVOIL,SPEC(7))
      COLID.(0,SPEC(8))
      DEN80 = COLDEN.(80.)
      FUELQ = HETVAL/360000.
      HEAD = 70.3863/DEN80 - .08333333333
      T'H COMPUT, FOR R = 0, 1, R .E. N
      S = R
      (I = 1, 1, I .E. 29, DAT(I) = DATA(S),
     1 CAL(I) = - 0., S = S + USE)
      W'R .NOT. LACK.(VCLEAR)
      W'R .NOT. LACK.(DAT(1)), CAL(1) = DAT(1)*DAT(2)/DYNAM(E)
      CAL(2) = BMEP(E)*DAT(2)
      E'L
      S = USE + R
      FUEL = FULFLO.(ID(S),DAT(3),DAT(4))
      AIR = AIRFLO.(ID(S+USE),DAT(6),DAT(5),DAT(8),DAT(9))
      W'R .NOT. LACK.(FUEL)
      CAL(3) = FUEL/CAL(1)
      CAL(4) = FUEL/AIR
      E'L
      PBAR = .4911570*DAT(8)
      VINJ = CYLVOL.(DAT(13))
      W'R .NOT. LACK2.(PBAR,DAT(9))
      CAL(8) = PBAR + .4911570*DAT(9)
      W'R .NOT. LACK.(DAT(10))
      CAL = CAL(8) + DAT(10)
```

```
          W'R .NOT. LACK.(DAT(11))
          CAL(12) = CAL + DAT(11)
          W'R .NOT. LACK2.(VIVC,VINJ),
         1    CAL(11) = ELOG.(CAL(12)/CAL)/ELOG.(VIVC/VINJ)
          E'L
          E'L
          E'L
          W'R .NOT. LACK.(DAT(1))
          CYCLES = 30.*DAT(1)
          CAL(5) = AIR/CYCLES
          RUN = ID(R)
          W'R RUN .GE. 1 .AND. RUN .LE. 74 .AND. LACK.(DAT(21))
          TBLO = DAT(24)
          O'E
          TBLO = DAT(21)
          E'L
          W'R .NOT. LACK.(DAT(7)), CAL(6) = 16.408644*
         1             SQRT.(BBLFT3.(TBLO,PBAR,.371110))*DAT(7)/CYCLES
          E'L
          W'R .NOT. LACK2.(VCLEAR,CAL(8))
          W'R .NOT. LACK.(CAL(5)),
         1    CAL(9) = EFF(E)*CAL(5)/BBLFT3.(DAT(16),CAL(8),.371110)
          W'R .NOT. LACK2.(CAL(4),DAT(19))
          REXH = (.371110 + CAL(4)/KEXH)/(1. + CAL(4))
          CAL(7) = BBLFT3.(DAT(19)+75.,CAL(8),REXH)*CLEAR
          W'R .NOT. LACK.(CAL(5))
          GAS = CAL(5) + CAL(7)
          RGAS = (CAL(5)*.371110 + CAL(7)*REXH)/GAS
          GAS = 1728.*GAS
          CAL(10) = BBFAR.(CAL,GAS/VIVC,RGAS)
          CAL(13) = GAS/VINJ
          CAL(14) = BBRAN.(CAL(12),CAL(13),RGAS)
          W'R .NOT. LACK3.(DAT(12),DAT(14),CAL(14))
          P = CAL(12)
          D = CAL(13)
          T = CAL(14)
          DEL = (DAT(14) - DAT(13))/10.
          FUELIN = 1728.*FUEL/CYCLES
          GASR = GAS*RGAS
          T'H DELAY, FOR I = 10, -1, I .E. 0
          VAPOR = PART(I)*FUELIN
          V'S PART(1) = .025, .050, .075, .100, .125, .150, .175, .200,
         1             .225, .250
          MIX = GAS + VAPOR
          RMIX = (GASR + VAPOR*RVAPOR)/MIX
          V = CYLVOL.(DAT(13) + I*DEL)
          D(I) = MIX/V
          W'R I .E. 10
          P(10) = CAL(12) + DAT(12)
          T(10) = BBRAN.(P(10),D(10),RMIX)
          INDEX = ELOG.(T(10)/T)/ELOG.(VINJ/V)
          CAL(15) = 1. + INDEX
          K = T*VINJ.P.INDEX
          O'E
          T(I) = K/V.P.INDEX
          P(I) = D(I)*RMIX*T(I)*BBCFAC.(D(I),T(I),RMIX)
DELAY     E'L
          CAL(16) = MEAN.(11,P,STORE)
          CAL(17) = MEAN.(11,D,STORE)
          CAL(18) = MEAN.(11,T,STORE)
```

```
         E'L
         E'L
         E'L
         E'L
         W'R .NOT. LACK.(DAT(13))
         CA = 166.6666667/DAT(1)
         W'R .NOT. LACK.(DAT(14)), CAL(19) = CA*(DAT(13) - DAT(14))
         W'R .NOT. LACK.(DAT(15)), CAL(20) = CA*(DAT(13) - DAT(15))
         E'L
         CAL(21) = THERMO.(DAT(17))
         W'R .NOT. LACK2.(CAL(21),DAT(18)),
        1  CAL(22) = THERMO.(DAT(17)+DAT(18)) - CAL(21)
         CAL(23) = .071165*DAT(23)
         W'R .NOT. LACK3.(DAT(21),DAT(22),HAVOIL), CAL(24) = .002228*
        1     OILDEN.(DAT(21)-DAT(22))*CAL(23)*
        2     OILCP.(DAT(21)-DAT(22)/2.)*DAT(22)
         W'R .NOT. LACK4.(DEN80,DAT(24),DAT(25),DAT(26))
         TCOLIN = DAT(24) - DAT(25)
         ROOTH = SQRT.(.1666666667 + DAT(26)*HEAD)
         NUCOL = COLNU.(TCOLIN)
         CAL(26) = 6.15836*ROOTH*(.5 +
        1           SQRT.(.25 + .010205*NUCOL/ROOTH))
         RN = 4391.75*CAL(26)/NUCOL
         W'R RN .G. 2000.
         CAL(27) = .002228*COLDEN.(TCOLIN)*CAL(26)*
        1           COLCP.(DAT(24)-DAT(25)/2.)*DAT(25)
         O'E
         CAL(26) = -0.
         E'L
         E'L
         W'R .NOT. LACK.(FUEL)
         QFUEL = FUELQ*FUEL
         CAL(25) = CAL(24)/QFUEL
         CAL(28) = CAL(27)/QFUEL
         E'L
         S = R
COMPUT   (I = 1, 1, I .E. 29, CALC(S) = CAL(I), S = S + USE)
         W'R MORE
         T'H COLMNS, FOR S = 0, USE, S .G. END28
COLMNS   AVEERR.(N,CALC(S))
         E'L
MORE1    BGNEND.(LINE,6,MAX,BGN,END,DONE1)
         W'R END .G. N, END = N
         P'T $12H-ENGINE WITHF6.2,12H/1 RATIO HASF7.4,27H CUIN CLEARAN
        1CE.  FUEL WITHF6.3,12H/1 RATIO HASF6.2,29H LBM/CUFT (@60) AND
        2 LIBERATESF6,9H BTU/LBM.*$,
        3  RATIO, VCLEAR, HTOC, DEN60, HETVAL
         P'T $129H0 FOR  BRAKE BMEP  BSFC FUEL/  CYCLE(LBM/1000) SURGE
        1 EFF @IVC  AT START OF INJECTION  AVERAGED DURING DELAY  DELA
        2Y(MSEC)  WALL(F)/129H  RUN   HP    PSI #/HRHP  AIR    AIR  BLO
        3W  EXH PSIA  PCT   F   INDEX PSIA #/CUFT  R   INDEX PSIA #/CU
        4FT  R   PRISE ILLUM  MIN INC/(I5,2F6.1,F6.3,F6.4,3PF7.2,3P2F5
        5.2,F5.1,F6.1,F4,2(F7.3,F5,F6.3,F5),F7.3,F6.3,F5,F4)*$,
        6  (R = BGN, 1, R .E. END, ID(R),
        7  (S = R, USE, S .G. END22, CALC(S)))
         T'O MORE1
DONE1    W'R MORE, P'T $5H MEAN2F6.1,F6.3,F6.4,3PF7.2,3P2F5.2,F5.1,F6.
        11,F4,2(F7.3,F5,F6.3,F5),F7.3,F6.3,F5,F4/5H ERRS2F6.1,F6.3,F6.
        24,3PF7.2,3P2F5.2,F5.1,F6.1,F4,2(F7.3,F5,F6.3,F5),F7.3,F6.3,F5
        3,F4*$, (R = N, 1, R .E. MAX,
```

```
           4  (S = R, USE, S .G. END22, CALC(S)))
MORE2       BGNEND.(LINE,4,MAX,BGN,END,DONE2)
            W'R END .G. N, END = N
            V'S OUT2 = $37H- FOR  CRANKCASE OILS  COOLANT SYSTEM/5H  RUN2
           1(16H  GPM BTU/SEC$, 601260346174K, $I5,F6.2,2F5.1,F6.1,2F5.1*
           2$
            P'T OUT2, (R = BGN, 1, R .E. END, ID(R),
           1  (S = USE22+R, USE, S .G. END28, CALC(S)))
            T'O MORE2
DONE2       W'R MORE, P'T $5H MEANF6.2,2F5.1,F6.1,2F5.1/5H ERRSF6.2,2F5.1
           1,F6.1,2F5.1*$, (R = N, 1, R .E. MAX,
           2  (S = USE22+R, USE, S .G. END28, CALC(S)))
            F'N LINE
            E'N
```

Computer Program 5

Title: Fuel Injection System Analysis

Purpose: To calculate the fuel mass flow rate, the accumulated injection and the average coefficient of discharge over the injection period.

Input: A sequence of needle lift, cylinder pressure, and fuel pressure, over the period of injection (are fed from oscilloscope traces).

Procedures:

1. Use ENGDAT to calculate the engine parameters
2. Use program AREAS to calculate the effective area of fuel flow
3. Calculate theoretical mass flow rate of fuel

$$Q = A\sqrt{2g(P_{fuel} - P_{cyl.})/\rho_{fuel}}$$

4. Calculate the theoretically accumulated injection over the injection period
5. Knowing the actual accumulated fuel/cycle from ENGCAL and the theoretical accumulated fuel/cycle, therefore an average coefficient of discharge is calculated.
6. Calculate the actual mass flow rate over the period of injection
7. Gives a printed, punched or plotted values of mass flow and accumulated injection over the injection period

Computer Program 5

Fuel Injection System Analysis

```
          D'N SPEC(19), ID(3), DATA(21), CALC(20), (DBTDC, NL, FP, CP,
         1    SAVE, AREA, LBMHR, D0, D1, D2, D3, D4, LBM)(1000),
         2    STORE(5000)
          EQUIVALENCE (SAVE, AREA), (STORE, D0, LBM), (STORE(1000), D1)
         1    ,(STORE(2000), D2), (STORE(3000), D3), (STORE(4000), D4)
          I'R IROUND., NUMDIV, BCDBN., NUMINT, NUMDAT, ENDDAT, NUMSEQ,
         1    ENDSEQ, I, FV, FVF, J, LINE, START, STOP, SPEC
          F'E FVF
AGAIN     ENGCAL.(1,SPEC,ID(1),DATA(1),CALC(1))
          P'T $1H-/1H0*$
          AREAS1.
          DENFUL = FULDEN.(SPEC(4),DATA(9))
          FUEL = FULFLO.(ID(2),DATA(3),DATA(4))/DATA(1)/30.
          R'T $S15,F16.10,S5,F16.10,S7,F16.10*$, BEGIN, EVERY, END
          NUMINT = BCDBN.(SPEC(7))
          NUMDAT = 1 + IROUND.((END - BEGIN)/EVERY)
          ENDDAT = 1 + NUMINT*NUMDAT
          NUMSEQ = ENDDAT - NUMINT
          W'R NUMSEQ .G. 1000, T'O FIN
          ENDSEQ = NUMSEQ + 1
          DELSEQ = EVERY/NUMINT
          DBTDC = BEGIN - DELSEQ
          (I = 1, 1, I .E. ENDSEQ,
         1 DBTDC(I) = DBTDC + I*DELSEQ)
          READ.(NL,2)
          READ.(FP,4)
          READ.(CP,4)
          LBMHR = SQRT.(DENFUL)/415.53855
          LBM = LBMHR/-21600./DATA(1)
          (I = 1, 1, I .E. ENDSEQ,
         1 P = FP(I) - CP(I),
         2 SAVE(I) = P/SQRT.(.ABS.P),
         3 LBMHR(I) = AREAS3.(NL(I))*SAVE(I))
          AREAS2.(FUEL/MEAN.(NUMSEQ,LBMHR(1),STORE(1))
         1            /(DBTDC(NUMSEQ)-DBTDC(1))/LBM)
          (I = 1, 1, I .E. ENDSEQ,
         1 AREA = AREAS3.(NL(I)),
         2 LBMHR(I) = AREA*SAVE(I),
         3 AREA(I) = AREA)
          DB4T11.(NUMSEQ,DELSEQ,1,LBMHR(1),D0(1),D1(1),D2(1),D3(1),
         1        D4(1))
          LBM(1) = -0.
          (I = 2, 1, I .E. ENDSEQ,
         1 J = I - 1,
         2 LBM(I) = LBM(J) + INTDER.(DBTDC(J),DBTDC(I),DBTDC(1),
         3                   NUMSEQ,DELSEQ,1,LBMHR(1),D1(1),
         4                   D2(1),D3(1),D4(1)))
          COEFF = FUEL/LBM(NUMSEQ)/LBM
          P'T $1H-/42H0FUEL DENSITY (@ TEMPERATURE OF COOLANT) =F6.2,43
         1H LBM/CUFT,  TOTAL FUEL INJECTED PER CYCLE =6PF7.2,12H LBM/10
         200000/1H-/50H-INTEGRATION OF DATA GIVES DISCHARGE COEFFICIENT
         3 =F7.4*$, DENFUL, FUEL, COEFF
          LBMHR = COEFF*LBMHR
          LBM = COEFF*LBM
          FUEL = FUEL/100.
          (I = 1, 1, I .E. ENDSEQ,
         1 LBMHR(I) = LBMHR*LBMHR(I),
         2 LBM(I) = LBM*LBM(I))
          LINE = 60
```

Computer Program 5 (Concluded)

```
MORE       BGNEND.(LINE,6,NUMDAT,START,STOP,DONE)
           ENDDAT = 1 + NUMINT*STOP
           P'T $1H-S8,48H|----DATA FROM SEQUENTIAL PHOTO ANALYSIS----|
           1|13(1H-)30HINCLUDES DISCHARGE COEFFICIENT12(1H-)1H|/132H0    A
           2T   NEEDLE LIFT   FUEL PRESSURE   CYLINDER PRESSURE   EQUIVALENT
           3 AREA   RATE OF INJECTION   ACCUMULATED INJECTION   FRACTION INJ
           4ECTED/7H   DBTDCS6,4HMILSS10,4HPSIAS12,4HPSIAS10,13HSQ IN/1000
           5000S7,8HLBM/HOURS12,11HLBM/1000000S14,3HPCT/(F7.1,F10.2,F14,F
           617.1,2F18.1,6PF21.2,F21.2)*$,
           7  (I = 1 + NUMINT*START, NUMINT, I .E. ENDDAT,
           8  DBTDC(I), NL(I), FP(I), CP(I), AREA(I), LBMHR(I), LBM(I),
           9  LBM(I)/FUEL)
           T'O MORE
DONE       W'R SPEC(8) .E. $PNCH$
           PUNCH FORMAT $I4,6HINJECT,5HBGN @F16.10,5H, FORF16.10,7H, END
           1 @F16.10,5H BTDC*$, ID(1), DBTDC(1), DELSEQ, DBTDC(NUMSEQ)
           PUNCH.(ID(1),$#/HR$,3,NUMSEQ,1,LBMHR(1))
           PUNCH.(ID(1),$#ACC$,-3,NUMSEQ,1,LBM(1))
           E'L
           T'O AGAIN
           I'N READ.(DAT,FV)
           FVF = 7 - FV
           R'T $S10,10F7.'FVF'*$, (I = 1, NUMINT, I .E. ENDDAT, DAT(I))
           INTERP.(NUMDAT,DBTDC(1),NUMINT,DAT(1))
           F'N
           E'N
FIN        E'M
```

Computer Program 6

Title: Calculation of Equivalent Area of Injection

Purpose: To calculate the effective area of injection at any needle lift, where effective area is the area to which we can write

$$Q = C_d A_{eff.} \sqrt{2g \frac{\Delta P}{\rho}}$$

Input:

1. Needle lift

2. An assumed value of coefficient of discharge

Procedure:

The pressure difference between fuel at inlet to injector and fuel out of the injector is measured. Due to the change in area between inlet and outlet an effective area was derived using the energy equation.

Computer Program 6

Equivalent Area of Injection as a Function of Injector-Needle Lift (AREAS)

```
     L'F
     EXTERNAL FUNCTION (ARG)
     D'N DIM(4)
     P'R PI(3.141592654)
     E'O AREAS1.
     R'T $4F10.5,F10.2,F10.4*$, DIM...DIM(4), COEFF
     AHOLES = PI*DIM*DIM*1.E6
     ABODY = PI*DIM(1)*DIM(1)*.25E6
     TAN = (DIM(2) - DIM(1))/2./DIM(3)
     ALPHA = ATAN.(TAN)
     COSINE = COS.(ALPHA)
     BETA = DIM(4)*PI/360.
     DIF = BETA - ALPHA
     RATIO = SIN.(BETA)/SIN.(DIF)
     K1 = PI*DIM(1)*DIF*RATIO*1000.
     K2 = 2.*PI*(DIF*COSINE*TAN + COS.(BETA) - COSINE)*RATIO*R TIO
     P T $132H-RATE OF INJECTION = DISCHARGE COEFFICIENT * EQUIVAL
    1ENT AREA * SQRT.(FUEL DENSITY * |FUEL PRESSURE - CYLINDER PRE
    2SSURE|) / 415.53855/14H    (LBM/HOUR)S32,13HSQ IN/1000000S11,
    310H(LBM/CUFT)S8,6H(PSIA)S12,6H(PSIA)/18H0INJECTOR HAS FOURF7.
    45,43H INCH HOLES,  CONTACT SURFACE HAS DIAMETERS F7.5,2H &F7.
    55,11H AND HEIGHTF7.5,15H,  TIP-ANGLE ISF7.2,8H DEGREES/132H0E
    6QUIVALENT AREA = 1/SQRT.(1/(OUTLET AREA FOR NEEDLE & SEAT).P.
    72 + 1/(AREA OF HOLES).P.2 - (DISCHARGE COEFFICIENT/AREA OF BO
    8DY).P.2)/S31,6HMILS*(F6.1,2H -F7.4,6H*MILS)F21.1,F44.1*$,
    9  DIM...DIM(4), K1, -K2, AHOLES, ABODY
     T'O SKIP
     E'O AREAS2.
     COEFF = ARG
SK   SQUARE = COEFF/ABODY
     SQUARE = 1./AHOLES/AHOLES - SQUARE*SQUARE
     F'N
     E'O AREAS3.
     MILS = ARG
     W'R MILS .LE. 0.
     F'N 0.
     O'E
     AOUT = MILS*(K1 + K2*MILS)
     F'N 1./SQRT.(1./AOUT/AOUT + SQUARE)
     E'L
     E'N
```

Computer Program 7

Title: Integration of a Given Data $Y_{(x)}$, Taken at Equal Intervals of x

Purpose: To apply numerical integration

Input:

1. Data to be integrated

2. Adjusted values of data and derivatives from applying DB4T11 (curve fitting program)

Procedure:

The given data are curve fitted with the best 5th degree polynomial for each point, the derivatives are found and used in expressing the function according to a Taylor series expansion that help in performing the integration.

Computer Program 7

Integration of Given Data (INTDER)

```
  L'F
  EXTERNAL FUNCTION INTDER.(FROM,TO,BGN,N,DEL,ADD,
1                                 D0,D1,D2,D3,D4)
  I'R LOWERI, UPPERI, N, ADD, ADDS, ENDI, I, AT
  DELX = DEL
  LOWERZ = (FROM - BGN)/DELX
  UPPERZ = (TO - BGN)/DELX
  W'R LOWERZ .G. UPPERZ
  ANSWER = LOWERZ
  LOWERZ = UPPERZ
  UPPERZ = ANSWER
  ANSWER = -1.
  O'E
  ANSWER = +1.
  E'L
  LOWERI = LOWERZ + .5
  UPPERI = UPPERZ + .5
  W'R LOWERI .L. 0 .OR. UPPERI .G. N - 1, ERROR RETURN
  LOWERZ = LOWERZ - LOWERI
  UPPERZ = UPPERZ - UPPERI
  ADDS = ADD
  LOWERI = LOWERI*ADDS
  UPPERI = UPPERI*ADDS
  ENDI = UPPERI - ADDS
  ZERO.(SUM0,SUM2,SUM4)
  (I = LOWERI + ADDS, ADDS, I .G. ENDI, SUM0 = SUM0 + D0(I),
1  SUM2 = SUM2 + D2(I), SUM4 = SUM4 + D4(I))
  F'N ANSWER*(ENDS.(.5,LOWERI) - ENDS.(LOWERZ,LOWERI) + DELX*
1     (SUM0 + DELX*DELX*(SUM2 + DELX*DELX*SUM4/80.)/24.) +
2     ENDS.(UPPERZ,UPPERI) - ENDS.(-.5,UPPERI))
  I'N ENDS.(Z,AT)
  X = Z*DELX
  I = AT
  F'N X*(D0(I) + X*(D1(I) + X*(D2(I) + X*(D3(I) + X*D4(I)
1     /5.)/4.)/3.)/2.)
  E'N
  E'N
```

Computer Program 8

Title: Best Straight Line to Fit a Group of Points

Purpose: To curve fit the given data Y according to the relation $Y = A+Bx$ and to give A, B, standard error in A, standard error in B, an estimate of standard error in data, standard errors in calculated values, adjusted values of Y, deviations of data from adjusted values and probability of occurrence of deviations.

Input: A sequence of Y data points at equally spaced intervals of x.

Procedure:

A least square best fitting straight line technique is applied to the given data.

Computer Program 8

Best Straight Line to Fit a Group of Points (BLINE)

```
AD (06 JAN 1967 VERSION) PROGRAM LISTING ... ... ...

              BLINE., CLINE., ELINE., DLINE., OLINE., WLINE.
              EXTERNAL FUNCTION (N,RESULT,X,Y)
              INTEGER N, GOOD, LAST, I, TYPE, BAD
              BOOLEAN NOPTS, SAMEX, NOERRS, LACK.
              DIMENSION ANSWER(5)
              ENTRY TO BLINE.
              GOOD = N
              LAST = GOOD - 1
              ZERO.(SUMX,SUMY,SUMXX,SUMXY,SUMYY)
              NOPTS = 1B
              SAMEX = 1B
              THROUGH SUMS, FOR I = 0, 1, I .G. LAST
              XI = X(I)
              YI = Y(I)
              WHENEVER LACK.(XI) .OR. LACK.(YI)
              GOOD = GOOD - 1
              OTHERWISE
              SUMX = SUMX + XI
              SUMY = SUMY + YI
              SUMXX = SUMXX + XI*XI
              SUMXY = SUMXY + XI*YI
              SUMYY = SUMYY + YI*YI
              WHENEVER SAMEX
              WHENEVER NOPTS
              NOPTS = 0B
              XFIRST = XI
              OTHERWISE
              SAMEX = XI .E. XFIRST
              END OF CONDITIONAL
              END OF CONDITIONAL
  SUMS        END OF CONDITIONAL
              NUM = GOOD
              DEL = NUM*SUMXX - SUMX*SUMX
              WHENEVER DEL .E. 0. .OR. SAMEX, ERROR RETURN
              ANSWER(1) = (SUMY*SUMXX - SUMX*SUMXY)/DEL
              ANSWER(1) = 0. + ANSWER(1)
              ANSWER(3) = (NUM*SUMXY - SUMX*SUMY)/DEL
              ANSWER(3) = 0. + ANSWER(3)
              NOERRS = GOOD .E. 2
              WHENEVER NOERRS
              OBS = -0.
              OTHERWISE
              OBS = (SUMYY - (SUMY*SUMY + ANSWER(3)*ANSWER(3)*DEL)
           1              /NUM)/(NUM - 2.)
              OBS = 0. + OBS
              END OF CONDITIONAL
              CAL = OBS/NUM
              AVE = SUMX/NUM
              MU = DEL/(NUM*NUM)
              ANSWER(0) = SQRT.(2.*CAL)
              ANSWER(2) = SQRT.(CAL*(1. + AVE*AVE/MU))
              ANSWER(4) = SQRT.(CAL/MU)
              ANSWER(5) = SQRT.(OBS)
              MOVER.(ANSWER...ANSWER(5),RESULT...RESULT(5))
```

```
            FUNCTION RETURN
            VECTOR VALUES FUNCT(1) = 0B, 0B, 0B, 0B, 0B
            ENTRY TO CLINE.
            TYPE = 1
            TRANSFER TO BEGIN
            ENTRY TO ELINE.
            TYPE = 2
            TRANSFER TO BEGIN
            ENTRY TO DLINE.
            TYPE = 3
            TRANSFER TO BEGIN
            ENTRY TO OLINE.
            TYPE = 4
            TRANSFER TO BEGIN
            ENTRY TO WLINE.
            TYPE = 5
            NOPTS = 1B
BEGIN       FUNCT(TYPE) = 1B
            LAST = N - 1
            WHENEVER .NOT. (FUNCT(1) .OR. FUNCT(3)) .AND. NOERRS
            WHENEVER FUNCT(5)
NOMAX       YDEV = -0.
            CALC = -0.
            BAD = -0
            TRANSFER TO END5
            OTHERWISE
            SPRAY.(-0.,RESULT...RESULT(LAST))
            TRANSFER TO END
            END OF CONDITIONAL
            END OF CONDITIONAL
            THROUGH ALLPTS, FOR I = 0, 1, I .G. LAST
            XI = X(I)
            WHENEVER LACK.(XI)
            CALC = -0.
            OTHERWISE
            YCAL = ANSWER(1) + ANSWER(3)*XI
            YCAL = 0. + YCAL
            WHENEVER FUNCT(1)
            CALC = YCAL
            OTHERWISE
            WHENEVER .NOT. FUNCT(3)
            ERR = XI - AVE
            ERR = CAL*(1. + ERR*ERR/MU)
            END OF CONDITIONAL
            WHENEVER FUNCT(2)
            CALC = SQRT.(ERR)
            CALC = 0. + CALC
            OTHERWISE
            YI = Y(I)
            WHENEVER LACK.(YI)
            CALC = -0.
            OTHERWISE
            YDEV = YI - YCAL
            YDEV = 0. + YDEV
            WHENEVER FUNCT(3)
            CALC = YDEV
            OTHERWISE
            DEV = YDEV*YDEV/(OBS + ERR)
            WHENEVER FUNCT(4)
            CALC = 100.*(1. - ERF.(SQRT.(DEV/2.)))
```

```
          OTHERWISE
          WHENEVER NOPTS
          NOPTS = 0B
          OTHERWISE
          WHENEVER DEV .L. MAXDEV, TRANSFER TO ALLPTS
          END OF CONDITIONAL
          MAXDEV = DEV
          BAD = I
          TRANSFER TO ALLPTS
          END OF CONDITIONAL
          END OF CONDITIONAL
          END OF CONDITIONAL
          END OF CONDITIONAL
          END OF CONDITIONAL
          END OF CONDITIONAL
          RESULT(I) = CALC
ALLPTS    CONTINUE
          WHENEVER FUNCT(5)
          WHENEVER NOPTS, TRANSFER TO NOMAX
          YDEV = Y(BAD) - ANSWER(1) - ANSWER(3)*X(BAD)
          YDEV = 0. + YDEV
          CALC = 100.*(1. - ERF.(SQRT.(MAXDEV/2.)))
          Y(BAD) = -0.
END5      FUNCT(5) = 0B
          RESULT(0) = YDEV
          RESULT(1) = CALC
          FUNCTION RETURN BAD
          OTHERWISE
END       FUNCT(TYPE) = 0B
          FUNCTION RETURN
          END OF CONDITIONAL
          END OF FUNCTION
```

Computer Program 9

Title: Curve Fitting (DB4T11)

Purpose: To reduce the effect of random errors in data.

Input: Data points at equal intervals

Procedure:

1. Read data

2. Statistically adjust the data to fit a 4th degree polynomial through 11 consecutive points by the use of Taylor's expansion up to the 5th term.

3. Give adjusted values of the middle point and the derivatives up to the 4th derivative. These derivatives are used for another program for integration.

Computer Program 9

Curve Fitting (DB4T11)

```
         L'F
         EXTERNAL FUNCTION DB4T11.(N,DEL,ADD,DATA,D0,D1,D2,D3,D4)
         I'R N, NUM, ADD, ADDS(5), I, J, STOP, P
         D'N (DELX,FACTOR,C)(4), (SUM,DIF)(5), K(6)
         B'N BEGIN
         NUM = N
         W'R NUM .L. 11, ERROR RETURN
         BEGIN = 1B
         V'S DELX = 1.
         V'S FACTOR = 1.
         ADDS(1) = ADD
         I = 1
         J = 0
CONSTS   DELX(I) = DEL*DELX(J)
         FACTOR(I) = I*FACTOR(J)/DELX(1)
         J = I
         I = I + 1
         ADDS(I) = ADDS(J) + ADDS(1)
         W'R I .L. 5, T'O CONSTS
         STOP = (NUM - 6)*ADDS(1)
         T'H INPTS, FOR P = ADDS(5), ADDS(1), P .G. STOP
         OBS = DATA(P)
         (I = 1, 1, I .G. 5, SUM = DATA(P + ADDS(I)), DIF =
       1 DATA(P - ADDS(I)), SUM(I) = SUM + DIF, DIF(I) = SUM - DIF)
         C(4) = (6.*(SUM(5) - SUM(4) - SUM(3) + OBS) - SUM(2) +
       1        4.*SUM(1))/3432.
         D4(P) = FACTOR(4)*C(4)
         C(3) = (30.*DIF(5) - 6.*DIF(4) - 22.*DIF(3) - 23.*DIF(2) -
       1        14.*DIF(1))/5148.
         D3(P) = FACTOR(3)*C(3)
         C(2) = (15.*SUM(5) + 6.*(SUM(4) - SUM(2)) - SUM(3) -
       1        9.*SUM(1) - 10.*OBS)/858. - 25.*C(4)
         D2(P) = FACTOR(2)*C(2)
         C(1) = (5.*DIF(5) + 4.*DIF(4) + 3.*DIF(3) + 2.*DIF(2) +
       1        DIF(1))/110. - 17.8*C(3)
         D1(P) = FACTOR(1)*C(1)
         C(0) = (SUM(5) + SUM(4) + SUM(3) + SUM(2) + SUM(1) +
       1        OBS)/11. - 10.*C(2) - 178.*C(4)
         D0(P) = C(0)
         W'R BEGIN, T'O ENDPTS
INPTS    C'E
         P = STOP
ENDPTS   K(0) = FACTOR(4)*C(4)
         K(1) = 2.*C(2)
         K(2) = 3.*C(3)
         K(3) = 4.*C(4)
         K(4) = 6.*C(3)
         K(5) = 12.*C(4)
         K(6) = 24.*C(4)
         T'H SERIES, FOR I = 1, 1, I .G. 5
         W'R BEGIN
         Z = - I
         J = P - ADDS(I)
         O'E
         Z = I
         J = P + ADDS(I)
         E'L
         D4(J) = K(0)
         D3(J) = (K(4) + Z*K(6))/DELX(3)
         D2(J) = (K(1) + Z*(K(4) + Z*K(5)))/DELX(2)
         D1(J) = (C(1) + Z*(K(1) + Z*(K(2) + Z*K(3))))/DELX(1)
SERIES   D0(J) = C(0) + Z*(C(1) + Z*(C(2) + Z*(C(3) + Z*C(4))))
         W'R BEGIN
         BEGIN = 0B
         T'O INPTS
         E'L
         F'N
         E'N
```

Computer Program 10

Title: Cylinder Volume and Gradient

Purpose: To calculate the cylinder volume and cylinder volume gradient at any crank angle.

Input: Crank angle to give corresponding cylinder volume and cylinder gradient.

Procedure:

A mathematical formula was derived including the effect of a slight wrist pin offset (center line of the wrist pin is offset from center line of the cylinder).

List of Assisting Program

1. Program to check for missing data (LACK)

Computer Program 10

Cylinder Volume and Gradient (CYLVOL, CYLGRA)

```
L'F
EXTERNAL FUNCTION (ARG1,ENGINE,SLEEVE)
I'R ENGINE, S, SLEEVE
B'N HAVEID, VOLUME, LACK.
V'S VCLEAR = 4.5610, 5.377, -0.
V'S RATIO = 16.69197512, 13.94055545, -0.
V'S DEL = .005333335856, 0.
V'S A = .25, .257292401
V'S B = .006666666667, 0.
V'S K1 = 183.4819679, 175.3861518
V'S K2 = 35.78470367, 34.79068412
V'S K3 = 143.1388147, 135.2184669
V'S K4 = .624560900, .607211986
E'O COMRAT.
W'R ENGINE .E. $ATAC$
S = 0
O'R ENGINE .E. $LIST$ .AND. SLEEVE .E. $NO.1$
S = 1
O'E
S = 2
E'L
HAVEID = S .NE. 2
ARG1 = VCLEAR(S)
F'N RATIO(S)
E'O CYLGRA.
VOLUME = 0B
E'O CYLVOL.
ALPHA = ARG1
W'R HAVEID .AND. .NOT. LACK.(ALPHA)
ALPHA = .01745329252*ALPHA - DEL(S)
SALPHA = SIN.(ALPHA)
CALPHA = COS.(ALPHA)
SBETA = A(S)*SALPHA + B(S)
CBETA = SQRT.(1. - SBETA*SBETA)
W'R VOLUME
ANSWER = K1(S) - K2(S)*CALPHA - K3(S)*CBETA
O'E
ANSWER = - K4(S)*(SALPHA + CALPHA*SBETA/CBETA)
E'L
O'E
ANSWER = - 0.
E'L
VOLUME = 1B
F'N ANSWER
E'N
```

Computer Program 11

Title: Cylinder Gas Properties

Purpose: To calculate the compressibility factor, temperature, and density of the gas, using the Beatti-Bridgeman equation of state.

Input:

1. Cylinder gas pressure and density, in order to calculate the average gas temperature.

2. Culinder gas pressure and temperature, in order to calculate the gas density.

Procedure:

1. To estimate the gas temperature at any crank angle, from the measured pressure, mass and cylinder volume, by using the perfect gas law.

2. To use the above estimated temperature to calculate the compressibility factor as obtained from the "Beatti-Bridgeman Equation"

$$P = \rho RT(1-\epsilon)(1+B\rho)-A\rho^2$$

where:

P = absolute cylinder pressure in psia

ρ = mass density in $lbsm/ft^3$

R = gas constant

T = gas temperature in degrees Rankine

$\epsilon = C\rho/T^3$

$B = B_o(1-b\rho)$

$A = A_o(1-a\rho)$

The constants for dry air are obtained from "Fundamentals of Classical Thermodynamics" by G. J. Van Wylen, and Richard E. Sonntag, John Wiley and Sons, Inc. New York, 1964, and converted to the British system as follows:

$C \approx 14.0 \times 10^4$

$B_o = 0.02550$

$b = -0.0006089$

$A_o = 5.8483$

$a = 0.01068$

R* for shop air = 0.371110 psi/(lbm/ft^3)°R

The value of Z from the above equation is as follows:

$$Z = (1 - \frac{C\rho}{T^3})(1+(B_o - B_o b\rho)\rho) - (A_o - A_o a\rho)\frac{\rho}{RT}$$

3. To use the above calculated compressibility factor to check temperature calculated in step 1.

4. To iterate the above steps until the final gas temperature calculated fulfills the Beatti-Bridgeman equation

List of Assisting Programs:

1. Program to check for missing data (LACK)

*The shop air is supplied at 98 psig and 80°F and assumed saturated with water pressure of 0.5 psi, i.e. water mole fraction of 0.004454. The correction due to water vapor is 0.2%

Computer Program 11

Cylinder Gas Properties (BBCFAC, BBRAN, BBFAR, BBLFT3)

```
          L'F
          EXTERNAL FUNCTION (ARG1,ARG2,RGAS)
          B'N LACK3., FAREN
          E'O BBCFAC.
          D = ARG1
          T = ARG2
          R = RGAS
          W'R LACK3.(D,T,R), T'O NOGOOD
          COMFAC.
          ANSWER = Z
          T'O RETURN
          E'O BBLFT3.
          T = ARG1
          P = ARG2
          R = RGAS
          W'R LACK3.(T,P,R), T'O NOGOOD
          T = T + 459.69
          DIDEAL = P/R/T
          D = DIDEAL
          COMFAC.
DNEXT     ZLAST = Z
          D = DIDEAL/ZLAST
          COMFAC.
          W'R .ABS.(Z - ZLAST) .G. 2E-8, T'O DNEXT
          ANSWER = D
          T'O RETURN
          E'O BBRAN.
          FAREN = 0B
          T'O SKIP
          E'O BBFAR.
          FAREN = 1B
SKIP      P = ARG1
          D = ARG2
          R = RGAS
          W'R LACK3.(P,D,R), T'O NOGOOD
          TIDEAL = P/D/R
          T = TIDEAL
          COMFAC.
TNEXT     ZLAST = Z
          T = TIDEAL/ZLAST
          COMFAC.
          W'R .ABS.(Z - ZLAST) .G. 2E-8, T'O TNEXT
          W'R FAREN, T = T - 459.69
          ANSWER = T
          T'O RETURN
NOGOOD    ANSWER = - 0.
RETURN    F'N ANSWER
          I'N COMFAC.
          Z = (1. - 14.0E4*D/T/T/T)*(1. + (.02550 + .00001553*D)*D) -
         1    (5.8483 - .06245*D)*D/R/T
          F'N
          E'N
          E'N
```

Computer Program 12

Title: Title Printing (TITLE)

Purpose: To print a title and read specifications to be used by other programs.

Input:

1. Required title

2. Specifications

Procedure:

The title and specifications are read according to a certain format the title is printed according to another format.

Computer Program 12

Title Printing (TITLE)

```
MAD (17 MAY 1967 VERSION) PROGRAM LISTING ... ... ...

            TITLE.
            EXTERNAL FUNCTION TITLE.(JOB,SPEC)
            DIMENSION ID(3), REMARK(19)
            BOOLEAN START, JOB, SPEC
            NORMAL MODE IS INTEGER
            WHENEVER START
            START = 0B
            VECTOR VALUES ID = 1
            ID(1) = S8.(0)
            TODAY.(ID(2),ID(3))
            ID(2) = ID(2) .LS. 18 .V. ID(2) .RS. 24 .V. $000 00$
            OR WHENEVER JOB
            ID = ID + 1
            END OF CONDITIONAL
            PRINT FORMAT $1H1/1H-S16,98HDIESEL ENGINE IGNITION AND COMBUSTION:  JA
          1 Y A. BOLT, N. A. HENEIN:  COMPUTER PROGRAM BY A. SNIVELY/88H
          2 ARMY CONTRACT NO. DA-20-018-AMC-1669T:  ORA PROJECT 06720:  C
          3 OMPUTER PROJECT NO. S986F:I3,8H OF JOB C6,15H:  COMPUTED ON C
          4 6,1H,C5*$, ID...ID(3)
            LINE = 8
            WHENEVER SPEC
            READ FORMAT $19C4,C3,I1*$, SPEC...SPEC(19), MORE
AGAIN       WHENEVER MORE .G. 0
            READ FORMAT $I1,19C4,C3*$, SPACE, REMARK...REMARK(19)
            HEAD = CARCON(SPACE)
            VECTOR VALUES CARCON = $1H+$, $1H $, $1H0$, $1H-$, $1H-/1H$
            VECTOR VALUES HEAD(1) = $ S26,19C4,C3*$
            PRINT FORMAT HEAD, REMARK...REMARK(19)
            LINE = LINE + SPACE
            MORE = MORE - 1
            TRANSFER TO AGAIN
            END OF CONDITIONAL
            END OF CONDITIONAL
            FUNCTION RETURN LINE
            END OF FUNCTION
```

Computer Program 13

Title: Fuel Properties

FULPRO (FUEL, HTOC, HETVAL)
FULDEN (FUEL, FAREN)
FULFLO (WEIGHT, MINUTS, LEAK)

Purpose:

FULPRO, to compute fuel properties
FULDEN, to compute fuel density
FULFLO, to compute rate of fuel flow

Usage:

A call on FULPRO, or FULDEN, must come first

Arguments:

FUEL = fuel identification (4 letter BCD)
HTDC = H/C atom ratio
HETVAL = heating value in Btu/lbm
FULPRO = fuel density at 60 °F in lbm/ft^3
FAREN = fuel temperature in °F
FULDEN = fuel density in lbm/ft^3
WEIGHT = timer weight identification (1 letter BCD)
MINUTS = fuel consumption time in min
LEAK = fuel leakage in liters/hr
FULFLO = rate of fuel flow in lbm/hr

Formulas:

$\rho 60° = 8824.90/(API + 131.5)$, $\rho = \rho 60°F - \Delta x(t-60)$
flow = LBM x 60/MINUTS - .03531542 x LEAK x $\rho 80°F$

Constants:

FUEL	HTOC	HETVAL	API	Δ	WEIGHT	LBM
\$SHOP\$	1.837	18370	34.79	.0235	\$A\$	.06262
\$NO.2\$	1.827	18500	39.51	.0239	\$B\$	.12667
\$MILG\$	2.141	18905	60.89	.0247	\$C\$	.25247
\$CT13\$	1.992	18705	49.37	.0252	\$D\$	.5007
\$CT19\$	1.999	18700	49.2	.0252	\$E\$	.9985
					\$F\$	.006262

Computer Program 13

Fuel Properties (FULHCR, FULDEN, FULFLO)

```
MAD (17 MAY 1967 VERSION) PROGRAM LISTING ... ... ...

               FULHCR., FULDEN., FULFLO.
               EXTERNAL FUNCTION(ID,VALUE1,VALUE2)
               INTEGER S, ID
               BOOLEAN LACK., LACK2., NOFUEL
               VECTOR VALUES FUEL = $SHOP$, $NO.2$, $MILG$, $CT13$, $CT19$
               VECTOR VALUES API = 34.79, 39.51, 60.89, 49.37, 49.2
               VECTOR VALUES T50 = 374., 516., 220., 370., 342.
               VECTOR VALUES DEL = .0235, .0239, .0247, .0252, .0252
               VECTOR VALUES LBM = 3.7572, 7.6002, 15.1482, 30.042, 59.910, .37572
               ENTRY TO FULHCR.
               FINDS.
               FUNCTION RETURN (1.5*API(S) - T50(S)/20. + 47.).P..3333333333/2.3498
               ENTRY TO FULDEN.
               FINDS.
               WHENEVER LACK.(VALUE1), TRANSFER TO ERRORS
               FUNCTION RETURN DEN60 - DEL(S)*(VALUE1 - 60.)
               ENTRY TO FULFLO.
               WHENEVER LACK2.(VALUE1,VALUE2) .OR. NOFUEL, TRANSFER TO ERRORS
               S = ID .RS. 30 - 17
               WHENEVER S .G. - 1 .AND. S .L. 6
               ANSWER = LBM(S)/VALUE1 - VALUE2*DEN80
               OTHERWISE
ERRORS         ANSWER = - 0.
               END OF CONDITIONAL
               FUNCTION RETURN ANSWER
               INTERNAL FUNCTION FINDS.
               NOFUEL = 0B
               THROUGH FUELS, FOR S = 0, 1, NOFUEL .OR. ID .E. FUEL(S)
FUELS          NOFUEL = S .G. 4
               WHENEVER NOFUEL, TRANSFER TO ERRORS
               DEN60 = 8824.90/(API(S) + 131.5)
               DEN80 = .03531542*(DEN60 - 20.*DEL(S))
               FUNCTION RETURN
               END OF FUNCTION
               END OF FUNCTION
```

Computer Program 14

Title: Coolant and Oil Properties

COLID (FAREN, ID)
COLNU (FAREN)
COLCP (FAREN)
COLDEN (FAREN)
OILID (FAREN, ID)
OILCP (FAREN)
OILDEN (FAREN)

Purpose:

COLID, OILID to find identification of coolent and oil respectively
COLNU, to find coolant kinematic viscosity
COLCP, OILCP to find specific heat for coolant and oil respectively
COLDEN, OILDEN to find density of coolant and oil respectively.

Usage:

A call on COLID must come before a call on COLNU or COLCP or COLDEN.
A call on OILID must come before a call on OILCP or OILDEN

Arguments:

FAREN = temperature in °F

ID = identification of coolant or oil. $EGLY$ for ethelene glycol; $MDV3$ for present oil DELVAC 1330

COLNU = coolant kinematic viscosity in centistokes
COLCP = coolant specific heat in Btu/lbm
COLDEN = coolant density in lbm/ft^3
OILCP = oil specific heat in Btu/lbm
OILDEN = oil density in lbm/ft^3
ARG1 = 1 if proper identification was used, = -0, if wrong identification, to be used by LACK.

Formulas:

For kinematic viscosity ν, $\ln\ln(\nu+.6) = A\ln(FAREN+459.69)+B$
For specific heat CP, CP = C+D*FAREN
For density ρ, ρ = E+F*FAREN

Constants:

ID	A	B	C	D	E	F
$EGLY$	-4.782178	31.144543	.518953	.0006237276	72.546342	-.0253698
$MDV3$	---	---	.540	.000	56.694196	-.0200661

Computer Program 14

Coolant and Oil Properties (COLID, OILID, COLDEN, OILDEN, COLCP, OILCP, COLNU)

```
MAD (17 MAY 1967 VERSION) PROGRAM LISTING ... ... ...

            COOLANT AND OIL PROPERTIES

            EXTERNAL FUNCTION(ARG1,ID)
            INTEGER ID, COL, OIL, S
            BOOLEAN HAVCOL, HAVOIL, COOLER, NU, CP, LACK.
            VECTOR VALUES A = -4.782178, 31.144543, .518933, .54, .0006237276, .0,
1              72.546342, 56.694196, -.0253698, -.0200661
            VECTOR VALUES HAVCOL = 0B
            VECTOR VALUES HAVOIL = 0B
            ENTRY TO COLID.
            WHENEVER ID .E. $EGLY$
            COL = 0
            OTHERWISE
            COL = 1
            END OF CONDITIONAL
            HAVCOL = COL .NE. 1
            FUNCTION RETURN
            ENTRY TO OILID.
            WHENEVER ID .E. $MDV3$
            OIL = 1
            ARG1 = 1.
            OTHERWISE
            OIL = 2
            ARG1 = -0.
            END OF CONDITIONAL
            HAVOIL = OIL .NE. 2
            FUNCTION RETURN
            ENTRY TO COLNU.
            COOLER = 1B
            NU = 1B
            TRANSFER TO BEGIN2
            ENTRY TO COLCP.
            COOLER = 1B
            TRANSFER TO SPHEAT
            ENTRY TO OILCP.
            COOLER = 0B
SPHEAT      CP = 1B
            TRANSFER TO BEGIN1
            ENTRY TO COLDEN.
            COOLER = 1B
            TRANSFER TO DENSTY
            ENTRY TO OILDEN.
            COOLER = 0B
DENSTY      CP = 0B
BEGIN1      NU = 0B
BEGIN2      T = ARG1
            WHENEVER (COOLER .AND. HAVCOL .OR. .NOT. COOLER .AND. HAVOIL)
1              .AND. .NOT. LACK.(T)
            WHENEVER COOLER
            S = COL
            OTHERWISE
            S = OIL
            END OF CONDITIONAL
            WHENEVER NU
            ANSWER = EXP.(EXP.(A(S)*ELOG.(T + 459.69) + A(S+1))) - .6
            TRANSFER TO END
            OR WHENEVER CP
            S = S + 2
            OTHERWISE
            S = S + 6
            END OF CONDITIONAL
            ANSWER = A(S) + A(S+2)*T
            OTHERWISE
            ANSWER = -0.
            END OF CONDITIONAL
END         FUNCTION RETURN ANSWER
            END OF FUNCTION
```

Computer Program 15

Title: Integral Mean Value of Given Data

MEAN (N, VALUES, STORE)

Purpose: To calculate the integral mean of a sequence

Arguments:

N = no of values (integer)
VALUES = sequence of values
STORE = region to store D0, D1, D2, D3, D4
MEAN = integral mean

Computer Program 15

Calculation of the Integral Mean Value of Given Data (MEAN)

MAD (17 MAY 1967 VERSION) PROGRAM LISTING ... ...

```
      MEAN.
      EXTERNAL FUNCTION MEAN.(N,VALUES,STORE)
      NORMAL MODE IS INTEGER
      FLOATING POINT INTDER., TO
      NUMBER = N
      BGN2 = NUMBER + NUMBER
      BGN3 = BGN2 + NUMBER
      BGN4 = BGN3 + NUMBER
      DB4T11.(NUMBER,1.,1,VALUES,STORE,STORE(NUMBER),STORE(BGN2),
 1            STORE(BGN3),STORE(BGN4))
      TO = NUMBER - 1
      FUNCTION RETURN INTDER.(0.,TO,0.,NUMBER,1.,1,VALUES,STORE(NUMBER),
 1            STORE(BGN2),STORE(BGN3),STORE(BGN4))/TO
      END OF FUNCTION
```

Computer Program 16

Title: Interpolating Program and Successive use of DB4T11 for Curve Fitting (INTERP), (USEDB4)

Purpose:

1. INTERP to give an interpolated value between data points

2. USEDB4 to use DB4T11 as many times as needed

Procedure:

A library subroutine is used for interpolating and an itterative use of DB4T11 is used for USEDB4.

Computer Program 16

Interpolation (INTERP)

MAD (06 JAN 1967 VERSION) PROGRAM LISTING ... ...

USEDB4., INTERP,

```
              EXTERNAL FUNCTION (N,X,ADD,DATA,BEST,NUMDB4)
              INTEGER NUMDB4, N, NUMDAT, ADD, NUMINT, I, NUMBER, STOPAT
              ENTRY TO USEDB4.
              WHENEVER NUMDB4 .G. 0
              NUMDAT = N
              DEL = X
              NUMINT = ADD
              DB4T11.(NUMDAT,DEL,NUMINT,DATA,BEST,BEST,BEST,BEST,BEST)
              THROUGH MORDB4, FOR I = 2, 1, I .G. NUMDB4
    MORDB4    DB4T11.(NUMDAT,DEL,NUMINT,BEST,BEST,BEST,BEST,BEST,BEST)
              FUNCTION RETURN
              OTHERWISE
              ERROR RETURN
              END OF CONDITIONAL
              ENTRY TO INTERP.
              NUMINT = ADD
              WHENEVER NUMINT .G. 1
              NUMDAT = N
              NUMBER = (NUMDAT - 1)*NUMINT
              THROUGH USETAB, FOR I = 1, 1, I .G. NUMBER
              STOPAT = I + NUMINT - 2
              THROUGH USETAB, FOR I = I, 1, I .G. STOPAT
    USETAB    DATA(I) = TAB.(X(I),X,DATA,NUMINT,NUMINT,5,NUMDAT,1.)
              END OF CONDITIONAL
              FUNCTION RETURN
              END OF FUNCTION
```

Computer Program 17

Title: Air Flow Rate

AIRFLO (ORF, TORF, PORF, PBAR, PINLET)

Purpose: To calculate rate of air flow

Arguments:

ORF = identification of orifice combination (1 letter BCD)
TORF = upstream temperature (before orifice) in °F
PROF = upstream pressure (before orifice) in psig
PBAR = barometric pressure in in. Hg
PINLET = pressure after orifice in in. Hg gauge
AIRFLO = air flow in lbm/hr

Formula:

$$\text{air flow} = B \frac{(\text{upstream pressure in psia - DEL})}{\sqrt{\text{upstream temperature in } ^{\circ}\text{R}}}$$

Constants:

ORF	B	DEL
1 ≡ #1	4.214	1.20
2 ≡ #2	8.255	0
3 ≡ #3	17.063	0
4 ≡ #4	32.642	0
5 ≡ #5	67.45	0
6 ≡ #5 and #1	71.67	.070
7 ≡ #5 and #2	75.71	0
8 ≡ #5 and #3	84.52	0
9 ≡ #5 and #4	100.10	0
A ≡ 3/32	12.766	1.72
B ≡ 1/8	23.229	1.61
C ≡ 3/16	51.74	.96
D ≡ 7/32	68.35	0
E ≡ D and A	81.11	.270
F ≡ D and B	91.58	.409
G ≡ D and C	120.08	.413
H ≡ D and C and A	132.85	.54
I ≡ D and C and B	143.31	.61
J ≡ D and C and B and A	156.08	.70

Computer Program 17

Air Flow Rate (AIRFLO)

```
MAD (17 MAY 1967 VERSION) PROGRAM LISTING ... ... ...

              AIRFLO.
              EXTERNAL FUNCTION AIRFLO.(ORF,TORF,PORF,PBAR,PINLET)
              INTEGER ORF, S
              BOOLEAN LACK4., LAST, ATAC
              VECTOR VALUES B = 4.214,  8.255,  17.063,  32.642,  67.45,  71.67,
            1         75.71,  84.52,  100.10,  12.766,  23.229,  51.74,
            2         68.35,  81.11,  91.58,  120.08,  132.85,  143.31,
            3         156.08
              VECTOR VALUES DEL = 1.20,  0.,  0.,  0.,  0.,  .070,  0.,  0.,  0.,
            1           1.72,  1.61,  .96,  0.,  .270,  .409,  .413,  .54,
            2           .61,  .70
              P = PORF
              BAR = PBAR
              WHENEVER LACK4.(TORF,P,BAR,PINLET), TRANSFER TO ERRORS
              P = P + .4911570*BAR
              WHENEVER P .L. .930*(PINLET + BAR), TRANSFER TO ERRORS
              S = ORF .RS. 30 - 1
              LAST = S .E. 32
              ATAC = LAST .OR. S .G. 15 .AND. S .L. 25
              WHENEVER ATAC
              WHENEVER LAST
              S = 18
              OTHERWISE
              S = S - 7
              END OF CONDITIONAL
              END OF CONDITIONAL
              WHENEVER S .G. - 1 .AND. S .L. 9 .OR. ATAC
              FLOW = B(S)*(P - DEL(S))/SQRT.(TORF + 459.69)
              OTHERWISE
     ERRORS   FLOW = -0.
              END OF CONDITIONAL
              FUNCTION RETURN FLOW
              END OF FUNCTION
```

Computer Program 18

Title: Average Values and Errors

AVE (N, VALUES)
RMS (N, VALUES)
AVEERR (N, VALUES)

Purpose:

AVE, to find the arithmetic average of a sequence
RMS, to find the RMS average of a sequence
AVEERR, to find the standard deviation of a sequence

Arguments:

N = number of values (INTEGER)
VALUES = sequence of values
AVE = arithmetic average of the nonlacking
RMS = square root of the mean of squares of the nonlacking
standard deviation of the nonlacking
AVEERR = VALUES (N) = AVE
VALUES (N+1) = AVEERR

Computer Program 18

Average Values and Errors (AVEERR)

```
MAD (17 MAY 1967 VERSION) PROGRAM LISTING ... ... ...

                   AVE., RMS., AVEERR.
                   EXTERNAL FUNCTION (N,VALUES)
                   INTEGER N, LAST, GOOD, S
                   BOOLEAN RMSERR, SQUARE, LACK., OKAY
                   VECTOR VALUES RMSERR = 0B
                   ENTRY TO AVEERR.
                   RMSERR = 1B
                   TRANSFER TO SKIP1
                   ENTRY TO RMS.
                   SQUARE = 1B
                   TRANSFER TO SKIP2
                   ENTRY TO AVE.
   SKIP1           SQUARE = 0B
   SKIP2           LAST = N
   BEGIN           GOOD = LAST
                   ANS = - 0.
                   THROUGH SUM, FOR S = 0, 1, S .E. LAST
                   VAL = VALUES(S)
                   WHENEVER LACK.(VAL)
                   GOOD = GOOD - 1
                   OTHERWISE
                   WHENEVER SQUARE, VAL = VAL*VAL
                   ANS = ANS + VAL
   SUM             END OF CONDITIONAL
                   OKAY = GOOD .G. 0
                   WHENEVER OKAY
                   ANS = ANS/GOOD
                   WHENEVER SQUARE, ANS = SQRT.(ANS)
                   ANS = 0. + ANS
                   END OF CONDITIONAL
                   WHENEVER RMSERR
                   WHENEVER .NOT. SQUARE
                   VALUES(LAST) = ANS
                   WHENEVER .NOT. OKAY, TRANSFER TO ERRORS
                   MEAN = ANS
                   SQUARE = 1B
                   TRANSFER TO BEGIN
                   OTHERWISE
                   ANS = SQRT.(.ABS. ((ANS - MEAN)*(ANS + MEAN)))
   ERRORS          VALUES(LAST+1) = ANS
                   RMSERR = 0B
                   END OF CONDITIONAL
                   END OF CONDITIONAL
                   FUNCTION RETURN ANS
                   END OF FUNCTION
```

Computer Program 19

Title: Cylinder Wall Temperature from Millivolt Readings

THERMO (MVOLTS)

Purpose: To find the Farenheit temperature corresponding to a millivolt reading of an iron-constantan thermocouple with reference at 32°F.

Arguments:

MVOLTS = millivolt difference from reference
THERMO = temperature in °F

Formula:

DB4T11, was used on data from the West Instrument Corporation to find the following formula (good within ± .1°F in the range from 32°F to 1015°F)

$$°F = 528.7948 + 324.3723 \times (\Delta\nu) + 2.1981 \times (\Delta\nu)^2 + 1.4488 \times (\Delta\nu)^3 - 2.0224 \times (\Delta\nu)^4$$

where $\Delta\nu$ =(millivolt - 15)/10.

Computer Program 19

Cylinder Wall Temperature from Millivolt Readings (THERMO)

MAD (11 MAY 1967 VERSION) PROGRAM LISTING ... ...

THERMO.

```
     EXTERNAL FUNCTION THERMO.(MVOLTS)
     BOOLEAN LACK.
     MV = MVOLTS
     WHENEVER LACK.(MV)
     FAREN = - 0.
     OTHERWISE
     MV = (MV - 15.)/10.
     FAREN = 528.7948 + MV*(324.3723 + MV*(2.1981 + MV*
1           (1.4488 - MV*2.0224)))
     END OF CONDITIONAL
     FUNCTION RETURN FAREN
     END OF FUNCTION
```

Computer Program 20

Title: Check on Missing Data

```
LACK (VALUE1)
LACK2(VALUE1, VALUE2)
LACK3 (VALUE1, VALUE2, VALUE3)
LACK4 (VALUE1, VALUE2, VALUE3, VALUE4)
LACK5 (VALUE1, VALUE2, VALUE3, VALUE4, VALUE5)
```

Purpose: To test for lacking values (i.e., a value of -0).

Action:

Value of function = 1B if any arguments are lacking
= 0B otherwise (none lacking)

Computer Program 20

Check on Missing Data (LACK)

```
MAD (17 MAY 1967 VERSION) PROGRAM LISTING ... ... ...

          LACK. , LACK2. , LACK3. , LACK4. , LACK5.
          EXTERNAL FUNCTION (VALUE1,VALUE2,VALUE3,VALUE4,VALUE5)
          DEFINE UNARY OPERATOR .LACKS., PRECEDENCE SAME AS .E.
          MODE STRUCTURE 2 = .LACKS. 0
JMP       *+18,AC,*+1
JMP       *+12,MQ,*+1
JMP       *+1,LA,*+18
JMP       *+1,BT,*+8
LAS       =4K11
TRA       LOC+2
TRA       LOC+3
PXD       0,0
TRA       LOC+2
CLA       =1
OUT       AC
SLW       T
JMP       *+8
JMP       *+1,BT,*+3
XCA
JMP       *+6
STQ       T
JMP       *+3
JMP       *+2,BT,*+1
STO       T
CLA       B
CAS       =4K11
TRA       LOC+2
TRA       LOC+3
PXD       0,0
TRA       LOC+2
CLA       =1
OUT       AC
END
          ENTRY TO LACK5.
          WHENEVER .NOT. .LACKS. VALUE5
          ENTRY TO LACK4.
          WHENEVER .NOT. .LACKS. VALUE4
          ENTRY TO LACK3.
          WHENEVER .NOT. .LACKS. VALUE3
          ENTRY TO LACK2.
          WHENEVER .NOT. .LACKS. VALUE2
          ENTRY TO LACK.
          FUNCTION RETURN .LACKS. VALUE1
          END OF CONDITIONAL
          END OF CONDITIONAL
          END OF CONDITIONAL
          END OF CONDITIONAL
          FUNCTION RETURN 1B
          END OF FUNCTION
                                                M'E 2 = .LACKS. 0        003
(THE NUMERIC FORM OF THE OPERATOR-MODE ARGUMENT IS     11400 )
```

Computer Program 21

Title: Rounding of Numbers

RNDOFF (VALUE, TD)
IROUND (VALUE)

Purpose:

RNDOFF, to find a round off of a value
IROUND, to find the nearest integer of a value

Arguments:

VALUE = value to be rounded
TO = precision of the round off (e.g. 1.0, .5, .1)
RNDOFF = rounded value
IROUND = nearest integer

Computer Program 21

Rounding of Numbers (IROUND)

MAD (17 MAY 1967 VERSION) PROGRAM LISTING ... ...

```
                    RNDOFF. , IROUND.
                    EXTERNAL FUNCTION (VALUE,TO)
                    INTEGER WHOLE
                    BOOLEAN FLOAT
                    ENTRY TO RNDOFF.
                    FLOAT = 1B
                    RONDTO = .ABS. TO
                    TRANSFER TO SKIP
                    ENTRY TO IROUND.
                    FLOAT = 0B
                    RONDTO = 1.
SKIP                ANSWER = VALUE
                    WHENEVER ANSWER .NE. 0.
                    WHOLE = ANSWER/RONDTO + .ABS. ANSWER/(ANSWER + ANSWER)
                    WHOLE = 0 + WHOLE
                    WHENEVER .NOT. FLOAT, FUNCTION RETURN WHOLE
                    ANSWER = WHOLE*RONDTO
                    END OF CONDITIONAL
                    FUNCTION RETURN ANSWER
                    END OF FUNCTION
```

Computer Program 22

Title: Axes Plotting

AXIS (XO, YO, AXLTH, THETA, AXSCAL, HGTH, TITLE)

Purpose: To either plot an axis (with tic marks) (with or without numbering) or to plot a centered title or both/neither.

Arguments:

XO, YO = coordinates in in. of the beginning of the axis

AXLTH = magnitude is the length of the axis in in., if positive, it is plotted from beginning to end, if negative, it is plotted from end to beginning.

THETA = counterclockwise degrees inclination from horizontal

AXSCAL
- (0) = value of axis variable at beginning of axis
- (1) = increase of axis variable per tic mark
- (2) = in. per tic mark on axis

HGHT = magnitude is height of numbers and letters in in. if positive, they are above the axis, if negative, they are below the axis

TITLE
- (0) = 0 to delet axis
- (D) = format for axis numbering (2-5 character BCD)
- (1) = no. of characters in title (INTEGER)
- (2)... = title to be plotted (BCD string)

Graphics:

Tic marks will be .075 in. on the side opposite title. Centerline of numbering will be HGHT from axis. Centerline of title will be 2.5*HGHT from axis. The numbering is centered about the 3rd position from left.

Axes Plotting (AXIS)

```
MAD (17 MAY 1967 VERSION) PROGRAM LISTING ... ... ...

               AXIS.
               EXTERNAL FUNCTION AXIS.(X0,Y0,AXLTH,THETA,AXSCAL,HGHT,TITLE)
               INTEGER NUMDIV, TITLE, FMT, NCHAR, CENTER, I
               BOOLEAN PLTAXI, PLTNMR, PLTBCD, BGNEND, LACK.
               FMT = TITLE
               PLTAXI = FMT .NE. 0
               HEIGHT = HGHT
               PLTNMR = HEIGHT .NE. 0.
               WHENEVER PLTNMR
               NCHAR = .ABS. TITLE(1)
               PLTBCD = NCHAR .G. 0
               OTHERWISE
               PLTBCD = 0B
               END OF CONDITIONAL
               WHENEVER PLTAXI .OR. PLTBCD
               LENGTH = AXLTH
               DELREL = AXSCAL(1)
               DELTIC = AXSCAL(2)
               BGNEND = LENGTH .L. 0.
               WHENEVER BGNEND
               LENGTH = - LENGTH
               DELREL = - DELREL
               DELTIC = - DELTIC
               END OF CONDITIONAL
               DEGREE = THETA
               RADIAN = DEGREE/57.29577951
               SINE = SIN.(RADIAN)
               COSINE = COS.(RADIAN)
               XABS = X0
               YABS = Y0
               XEND = XABS + LENGTH*COSINE
               YEND = YABS + LENGTH*SINE
               NUMDIV = (LENGTH + .0001)/ .ABS. DELTIC
               ABSHGT = .ABS. HEIGHT
               WHENEVER PLTBCD
               CENTER = (NUMDIV + 1)/2
               XDEL = - (NCHAR/2)*.8571428571*ABSHGT
               YDEL = 2.5*HEIGHT - .5*ABSHGT
               XBCD = .5*(XABS + XEND) + XDEL*COSINE - YDEL*SINE
               YBCD = .5*(YABS + YEND) + XDEL*SINE + YDEL*COSINE
               END OF CONDITIONAL
               WHENEVER PLTAXI
               WHENEVER PLTNMR
               XDEL = - 2.*ABSHGT
               YDEL = HEIGHT - .5*ABSHGT
               XNMR = XDEL*COSINE - YDEL*SINE
               YNMR = XDEL*SINE + YDEL*COSINE
               XREL = AXSCAL
               FMT = FMT .RS. 6 .LS. 6 .V. $00000*$
               END OF CONDITIONAL
               XTIC = .075*SINE
               YTIC = - .075*COSINE
               WHENEVER LACK.(HEIGHT - HEIGHT)
               XTIC = - XTIC
```

```
          YTIC = - YTIC
          END OF CONDITIONAL
          XDEL = DELTIC*COSINE
          YDEL = DELTIC*SINE
          I = 0
          WHENEVER .NOT. BGNEND
          PENUP.(XABS,YABS)
          OTHERWISE
          PENUP.(XEND,YEND)
          NUMBER = NUMDIV
          WHENEVER PLTNMR, XREL = XREL - NUMBER*DELREL
          XABS = XABS - NUMBER*XDEL
          YABS = YABS - NUMBER*YDEL
NXTDIV    PENDN.(XABS,YABS)
          END OF CONDITIONAL
          PENDN.(XABS+XTIC,YABS+YTIC)
          WHENEVER PLTNMR
          PNUMBR.(XABS+XNMR,YABS+YNMR,ABSHGT,XREL,DEGREE,FMT)
          XREL = XREL + DELREL
          WHENEVER I .E. CENTER .AND. PLTBCD
          PSYMB.(XBCD,YBCD,ABSHGT,TITLE(2),DEGREE,NCHAR)
          PLTBCD = 0B
          END OF CONDITIONAL
          END OF CONDITIONAL
          PENUP.(XABS,YABS)
          WHENEVER I .L. NUMDIV
          I = I + 1
          XABS = XABS + XDEL
          YABS = YABS + YDEL
          TRANSFER TO NXTDIV
          END OF CONDITIONAL
          WHENEVER .NOT. BGNEND, PENDN.(XEND,YEND)
          OTHERWISE
          PSYMB.(XBCD,YBCD,ABSHGT,TITLE(2),DEGREE,NCHAR)
          END OF CONDITIONAL
          END OF CONDITIONAL
          FUNCTION RETURN
          END OF FUNCTION
```

Computer Program 23

Title: Curve Plotting

GRAPH (SCALES, XTITLE, YTITLE, TITLE)

Purpose: To prepare a graph for data plotting, including output media specifications, coordinate system quantification axes with respective titles and numbering at tic marks, and an overall title.

Arguments:

SCALES	(0), (1), (2) = AXSCAL for X axis	
	(3), (4), (5) = AXSCAL for Y axis	see
XTITLE = TITLE for X axis		AXIS
YTITLE = TITLE for Y axis		
TITLE	(0) = no. of characters in overall title (INTEGER)	
	(1)...(N) = overall title (BCD string)	

Graphics:

The axes are chosen to begin at (.65, .41) in. No. of X divisions are such as to use most of 14.000 in. No. of Y divisions are such as to use most of 10.333 in. The border with tic marks is completed on the other 2 sides. Numbering and lettering are done with a height of .13 in. TITLE is treated as a 2nd YTITLE. The above restrict XTITLE to 125 characters (23 words), YTITLE to 92 characters (18 words), TITLE to 92 characters (17 words).

Computer Program 23

Curve Plotting (GRAPH)

```
MAD (17 MAY 1967 VERSION) PROGRAM LISTING ... ... ...

          GRAPH.
          EXTERNAL FUNCTION GRAPH.(SCALES,XTITLE,YTITLE,TITLE)
          VECTOR VALUES YFMT(1) = 0
          INTEGER NUMDIV, NCHAR, YTITLE, TITLE
          PLTPAP.($400$)
          PLTXMX.(14.90)
          XTIC = SCALES(2)
          YTIC = SCALES(5)
          PLTOFS.(SCALES,SCALES(1)/XTIC,SCALES(3),SCALES(4)/YTIC,.65,
                 .41)
          NUMDIV = 14.0001/XTIC
          XLTH = NUMDIV*XTIC
          NUMDIV = 10.3334/YTIC
          YLTH = NUMDIV*YTIC
          YFMT = YTITLE
          AXIS.(.65,.41,XLTH,0.,SCALES,-.13,XTITLE)
          AXIS.(XLTH+.65,.41,YLTH,90.,SCALES(3),-.13,YFMT)
          AXIS.(.65,YLTH+.41,-XLTH,0.,SCALES,0.,XTITLE)
          AXIS.(.65,.41,-YLTH,90.,SCALES(3),.13,YTITLE)
          NCHAR = TITLE
          WHENEVER NCHAR .G. 0, PSYMB.(.195,.41+YLTH/2.-(NCHAR/2)*
                            .1114285714,.13,TITLE(1),90.,NCHAR)
          FUNCTION RETURN
          END OF FUNCTION
```

Computer Program 24

Title: Results Punching (PUNCH)

Purpose: To punch a given sequence of points according to a given format.

Input: Sequence of values that are required to be punched.

Computer Program 24

Results Punching (PUNCH)

```
MAD (17 MAY 1967 VERSION) PROGRAM LISTING ... ... ...

            PUNCH.
            EXTERNAL FUNCTION PUNCH.(RUN,ID,BEFORE,N,ADD,VALUES)
            NORMAL MODE IS INTEGER
            FORMAT VARIABLE FV
            ADDS = ADD
            ADDTEN = 10*ADDS
            IEND = N*ADDS
            FV = 7 - BEFORE
            PUNCH FORMAT $I4,I2,C4,'FV'P1OF7*$,
          1   (I = 0, ADDTEN, I .GE. IEND, RUN, CARD.(I), ID,
          2   (J = I, ADDS, J .E. JEND, VALUES(J)))
            FUNCTION RETURN
            INTERNAL FUNCTION CARD.
            JEND = I + ADDTEN
            WHENEVER JEND .G. IEND, JEND = IEND
            FUNCTION RETURN 1 + I/ADDTEN
            END OF FUNCTION
            END OF FUNCTION
```

APPENDIX B

TABLES

TABLE 1

EFFECT OF ENGINE SPEED ON IGNITION DELAY USING CITE FUEL AT A MEAN PRESSURE OF 500 PSIA DURING THE IGNITION DELAY

IATA SET A4A HAS 5 RUNS. THE ATAC ENGINE (SLEEVE, IVC @ 128 DBTDC) USED CT19 FUEL (3000 PSI), MDV3 OIL, AND H2O COOLANT.

FOR RUN	USE W	O	SPEED RPM	LOAD LBS	FUEL MIN	L/HR	AIR PSIG	F	BLOW CFPM	ROOM- INHG	SURGE- INHG	@IVC- PSI	@INJ- PSI	RIS PSI	DBTDC LIFT	AT START OF RISE	ILLUM	AIR F	MILLVOLTS MIN	INC	EXHAUST F	FU
71	C	C	1000	21.8	8.17	.18	34.0	75	.6	28.9	10.7	3.1	436	213	20.7	11.3	9.4	96	-.0	-.00	622	14
72	C	C	1500	17.8	5.96	.30	51.2	73	.6	29.1	6.8	3.3	401	276	21.0	8.3	6.0	91	-.0	-.00	657	49
73	C	C	2000	13.1	5.01	.27	66.6	76	.8	29.2	3.6	4.0	386	312	20.9	5.1	2.6	94	-.0	-.00	691	51
74	E	D	2400	11.0	9.12	.29	51.5	76	.8	29.1	1.5	2.9	360	316	21.4	3.3	-.0	93	-.0	-.00	699	52
70	D	D	2800	9.5	3.73	.25	57.6	78	-.0	29.3	.0	2.7	360	288	20.5	1.2	-.0	91	-.0	-.00	746	-0
MEAN			1940	14.6	6.40	.26	52.2	76	.7	29.1	4.5	3.2	389	281	20.9	5.8	6.0	93	-.0	-.00	683	42
ERRS			637	4.5	1.99	.04	10.7	2	.1	.1	3.8	.4	28	37	.3	3.6	2.8	2	-.0	-.00	42	16

FOR RUN	CRANKCASE OILS OUT(F)	INC	CPS	COOLANT SYSTEM OUT(F)	INC	INHG	CYL HD WALL TEMP INT.(F)	EXH.(F)
71	-.0	-.0	-0	168.0	-.0	-.0	-.0	-.0
72	-.0	-.0	-0	171.0	-.0	-.0	-.0	-.0
73	-.0	-.0	-0	172.0	-.0	-.0	-.0	-.0
74	-.0	-.0	-0	171.0	-.0	-.0	-.0	-.0
70	-.0	-.0	-0	170.0	-.0	-.0	-.0	-.0
MEAN	-.0	-.0	-0	170.4	-.0	-.0	-.0	-.0
ERRS	-.0	-.0	-0	1.4	-.0	-.0	-.0	-.0

ENGINE WITH 16.69/1 RATIO HAS 4.5610 CUIN CLEARANCE. FUEL WITH 1.999/1 RATIO HAS 48.84 LBM/CUFT (@60) AND LIBERATES 18700 BTU/LBM.

FOR RUN	BRAKE HP	BMEP PSI	BSFC #/HRHP	FUEL/ AIR	CYCLE(LBM/1000) AIR	BLOW	EXH	SURGE PSIA	EFF PCT	@IVC F	AT START OF INJECTION INDEX	PSIA	#/CUFT	R	AVERAGED DURING DELAY INDEX	PSIA	#/CUFT	R	DELAY(MSEC) PRISE	ILLUM	WALL(F) MIN	INC
71	7.3	80.4	.464	.0319	3.52	.08	.12	19.4	90.2	170	1.387	459	.847	1441	1.193	563	1.006	1488	1.567	1.883	-0	-0
72	8.9	65.7	.509	.0313	3.21	.05	.11	17.6	89.9	182	1.390	422	.763	1473	1.234	559	.958	1549	1.411	1.667	-0	-0
73	8.7	48.3	.634	.0310	2.98	.05	.09	16.1	91.7	206	1.388	406	.709	1526	1.227	567	.930	1619	1.317	1.525	-0	-0
74	8.8	40.6	.690	.0313	2.70	.05	.09	15.0	88.9	195	1.420	378	.631	1598	1.204	547	.856	1696	1.257	-.000	-0	-0
70	8.9	35.0	.860	.0359	2.53	-.00	.08	14.4	86.6	208	1.419	377	.610	1649	1.169	541	.830	1733	1.149	-.000	-0	-0
MEAN	8.5	54.0	.631	.0323	2.99	.06	.10	16.5	89.5	192	1.401	408	.712	1537	1.205	555	.916	1617	1.340	1.692	-0	-0
ERRS	.6	16.8	.141	.0019	.36	.01	.01	1.8	1.7	14	.015	30	.087	77	.024	10	.065	90	.142	.147	-0	-0

TABLE 2

EFFECT OF ENGINE SPEED ON IGNITION DELAY USING CITE FUEL AT A MEAN PRESSURE OF 700 PSIA DURING THE IGNITION DELAY

DATA SET A4B HAS 5 RUNS. THE ATAC ENGINE (SLEEVE, IVC @ 128 DBTDC) USED CT19 FUEL (3000 PSI), MDV3 OIL, AND EGLY COOLANT.

FOR RUN	USE W	USE O	SPEED RPM	LOAD LBS	FUEL MIN	FUEL L/HR	AIR PSIG	AIR F	BLOW CFPM	ROOM- INHG	SURGE- INHG	@IVC- PSI	@INJ- PSI	RIS PSI	DBTDC LIFT	AT START OF RISE	AT START OF ILLUM	AIR F	MILLVOLTS MIN	MILLVOLTS INC	EXHAUST F	EXHAUST HU
86	C	C	1000	27.6	5.74	.55	48.5	76	.7	29.3	22.9	1.1	552	212	20.8	13.6	-.0	96	12.1	1.13	789	72
87	E	C	1500	26.6	8.54	.57	73.0	81	.7	29.3	18.7	1.0	532	276	20.8	11.0	-.0	96	13.4	1.15	813	40
88	E	D	2000	22.9	6.95	.60	67.5	79	.7	29.2	15.1	1.0	513	340	20.8	8.0	-.0	95	14.3	1.01	843	48
89	E	E	2500	18.8	5.82	.79	67.1	80	.7	29.3	12.7	1.0	513	363	20.5	5.8	-.0	93	14.3	.82	873	52
90	E	E	2899	13.9	5.52	.80	72.2	82	.9	29.1	10.6	3.0	477	370	21.0	5.1	-.0	101	14.4	.40	931	60
MEAN			1980	22.0	6.51	.66	65.7	80	.7	29.2	16.0	1.4	517	312	20.8	8.7	-.0	96	13.7	.90	850	54
ERRS			679	5.1	1.13	.11	8.9	2	.1	.1	4.4	.8	25	60	.2	3.2	-.0	3	.9	.28	49	11

FOR RUN	CRANKCASE OILS OUT(F)	CRANKCASE OILS INC	CRANKCASE OILS CPS	COOLANT SYSTEM OUT(F)	COOLANT SYSTEM INC	COOLANT SYSTEM INHG	CYL HD WALL TEMP INT.(F)	CYL HD WALL TEMP EXH.(F)
86	178.3	2.2	49	178.8	7.0	.8	269.2	325.9
87	195.3	2.2	55	176.7	5.4	2.0	264.0	336.3
88	205.2	2.2	60	176.2	4.3	3.7	264.9	350.1
89	207.1	4.9	67	175.9	4.1	5.9	268.5	351.8
90	211.1	7.8	80	171.5	2.5	8.3	270.7	360.8
MEAN	199.4	3.9	62	175.8	4.7	4.1	267.5	345.0
ERRS	11.8	2.2	11	2.4	1.5	2.7	2.6	12.3

ENGINE WITH 16.69/1 RATIO HAS 4.5610 CUIN CLEARANCE. FUEL WITH 1.999/1 RATIO HAS 48.84 LBM/CUFT (@60) AND LIBERATES 18700 BTU/LBM.

FOR RUN	BRAKE HP	BMEP PSI	BSFC #/HRHP	FUEL/ AIR	CYCLE(LBM/1000) AIR	CYCLE(LBM/1000) BLOW	CYCLE(LBM/1000) EXH	SURGE PSIA	EFF PCT	@IVC F	AT START OF INJECTION INDEX	AT START OF INJECTION PSIA	AT START OF INJECTION #/CUFT	AT START OF INJECTION R	AVERAGED DURING DELAY INDEX	AVERAGED DURING DELAY PSIA	AVERAGED DURING DELAY #/CUFT	AVERAGED DURING DELAY R	DELAY(MSEC) PRISE	DELAY(MSEC) ILLUM	WALL(F) MIN	WALL(F) INC
86	9.2	101.8	.467	.0310	4.61	.09	.14	25.6	89.6	113	1.418	579	1.101	1395	1.225	682	1.259	1436	1.200	-.000	435	37
87	13.3	98.1	.454	.0314	4.27	.06	.12	23.6	90.2	109	1.439	557	1.019	1450	1.209	691	1.219	1503	1.089	-.000	477	37
88	15.3	84.5	.498	.0315	4.02	.05	.11	21.8	91.7	101	1.457	536	.956	1488	1.203	705	1.200	1555	1.067	-.000	506	33
89	15.7	69.4	.571	.0315	3.78	.04	.10	20.6	90.7	107	1.472	535	.910	1561	1.177	721	1.171	1630	.980	-.000	506	27
90	13.4	51.3	.706	.0316	3.46	.04	.09	19.5	89.0	185	1.434	499	.816	1628	1.181	691	1.072	1707	.914	-.000	509	13
MEAN	13.4	81.0	.539	.0314	4.03	.06	.11	22.2	90.2	123	1.444	541	.960	1504	1.199	698	1.184	1566	1.050	-.000	487	29
ERRS	2.3	18.8	.093	.0002	.40	.02	.02	2.2	.9	31	.019	26	.096	82	.018	14	.063	95	.098	-.000	28	9

FOR RUN	CRANKCASE OILS GPM	CRANKCASE OILS BTU/SEC	CRANKCASE OILS %	COOLANT SYSTEM GPM	COOLANT SYSTEM BTU/SEC	COOLANT SYSTEM %
86	3.49	.5	2.2	6.0	4.0	18.1
87	3.91	.5	1.7	8.9	4.6	14.6
88	4.27	.6	1.5	11.8	4.8	12.3
89	4.77	1.5	3.2	14.7	5.8	12.4
90	5.69	2.8	5.7	17.4	4.1	8.4
MEAN	4.43	1.2	2.9	11.8	4.7	13.1
ERRS	.76	.9	1.5	4.0	.6	3.2

TABLE 3

EFFECT OF COOLANT TEMPERATURE ON IGNITION DELAY

DATA SET A5A HAS 8 RUNS. THE ATAC ENGINE (SLEEVE, IVC @ 128 DBTDC) USED CT19 FUEL (3000 PSI), MDV3 OIL, AND EGLY COOLANT.

FOR RUN	USE W	USE O	SPEED RPM	LOAD LBS	FUEL MIN	FUEL L/HR	AIR PSIG	AIR F	BLOW CFPM	ROOM- INHG	SURGE- INHG	@IVC- PSI	@INJ- PSI	RIS PSI	DBTDC LIFT	AT START OF RISE	AT START OF ILLUM	AIR F	MILLVOLTS MIN	MILLVOLTS INC	EXHAUST F	EXHAUST HU
75	E	E	2000	27.6	5.65	.76	71.0	75	.8	28.9	40.2	7.5	778	338	21.0	12.8	-.0	253	-.0	-.00	846	60
76	E	E	2002	26.5	5.66	.81	70.8	76	1.0	28.9	40.2	5.9	774	342	21.0	12.8	-.0	255	-.0	-.00	840	59
80	E	E	2000	28.3	5.53	.84	71.4	85	1.0	29.3	40.1	6.8	780	338	21.0	13.0	-.0	253	-.0	-.00	905	56
79	E	E	2000	27.2	5.50	.88	71.4	84	1.0	29.3	39.9	6.8	774	341	21.1	13.0	-.0	252	-.0	-.00	902	54
78	E	E	2000	27.1	5.53	.90	71.1	84	1.1	29.2	39.9	8.7	774	333	20.9	12.9	-.0	255	-.0	-.00	913	58
77	E	E	2000	24.4	5.54	.91	70.9	84	1.1	29.3	40.2	8.2	782	339	20.9	12.7	-.0	257	-.0	-.00	921	74
81	E	E	1999	28.9	5.51	.92	71.1	79	1.0	29.4	40.0	8.4	760	350	21.0	12.5	-.0	253	-.0	-.00	950	48
82			-0	22.8	-.00	.95	-.0	-0	.9	-.0	-.0	-.0	-0	-0	-.0	-.0	-.0	-0	-.0	-.00	-0	66
MEAN			2000	26.6	5.56	.87	71.1	81	1.0	29.2	40.1	7.5	775	340	21.0	12.8	-.0	254	-.0	-.00	897	59
ERRS			1	1.9	.06	.06	.2	4	.1	.2	.1	.9	7	5	.1	.2	-.0	2	-.0	-.00	37	7

FOR RUN	CRANKCASE OILS OUT(F)	CRANKCASE OILS INC	CRANKCASE OILS CPS	COOLANT SYSTEM OUT(F)	COOLANT SYSTEM INC	COOLANT SYSTEM INHG	CYL HD WALL TEMP INT.(F)	CYL HD WALL TEMP EXH.(F)
75	192.5	3.5	72	156.6	6.6	3.7	-.0	-.0
76	199.3	3.1	73	187.0	6.0	3.8	-.0	-.0
80	205.9	4.0	73	217.0	5.6	3.5	-.0	-.0
79	206.9	4.4	75	246.0	4.8	3.6	-.0	-.0
78	209.0	6.0	77	276.1	4.7	3.6	-.0	-.0
77	210.5	7.1	76	304.3	2.9	3.6	-.0	-.0
81	211.8	7.7	75	305.0	3.3	3.9	-.0	-.0
82	-.0	-.0	-0	-.0	-.0	-.0	-.0	-.0
MEAN	205.1	5.1	74	241.7	4.8	3.7	-.0	-.0
ERRS	6.4	1.7	2	53.4	1.3	.1	-.0	-.0

ENGINE WITH 16.69/1 RATIO HAS 4.5610 CUIN CLEARANCE. FUEL WITH 1.999/1 RATIO HAS 48.84 LBM/CUFT (@60) AND LIBERATES 18700 BTU/LBM.

FOR RUN	BRAKE HP	BMEP PSI	BSFC #/HRHP	FUEL/ AIR	CYCLE(LBM/1000) AIR	CYCLE(LBM/1000) BLOW	CYCLE(LBM/1000) EXH	SURGE PSIA	EFF PCT	@IVC F	AT START OF INJECTION INDEX	AT START OF INJECTION PSIA	AT START OF INJECTION #/CUFT	AT START OF INJECTION R	AVERAGED DURING DELAY INDEX	AVERAGED DURING DELAY PSIA	AVERAGED DURING DELAY #/CUFT	AVERAGED DURING DELAY R	DELAY(MSEC) PRISE	DELAY(MSEC) ILLUM	WALL(F) MIN	WALL(F) INC
75	18.4	101.8	.506	.0312	4.96	.05	.17	33.9	93.5	360	1.381	819	1.182	1832	1.197	984	1.376	1885	.683	-.000	-0	-0
76	17.7	97.8	.520	.0310	4.94	.07	.18	33.9	93.3	332	1.396	814	1.177	1827	1.216	980	1.371	1885	.683	-.000	-0	-0
80	18.9	104.4	.498	.0316	4.95	.07	.17	34.1	92.8	352	1.388	821	1.178	1841	1.222	985	1.367	1900	.667	-.000	-0	-0
79	18.1	100.3	.518	.0316	4.96	.07	.17	34.0	93.1	349	1.388	815	1.174	1833	1.223	980	1.366	1893	.675	-.000	-0	-0
78	18.1	100.0	.515	.0314	4.94	.07	.17	33.9	93.2	389	1.364	817	1.178	1831	1.215	979	1.367	1888	.667	-.000	-0	-0
77	16.3	90.0	.569	.0313	4.93	.07	.17	34.1	92.8	385	1.371	824	1.176	1852	1.197	989	1.369	1905	.683	-.000	-0	-0
81	19.3	106.6	.483	.0312	4.97	.07	.16	34.1	93.1	382	1.360	802	1.180	1797	1.216	973	1.382	1856	.709	-.000	-0	-0
82	-.0	84.1	-.000	-.0000	-.00	-.00	-.00	-.0	-.0	-0	-.000	-0	-.000	-0	-.000	-0	-.000	-0	-.000	-.000	-0	-0
MEAN	18.1	98.1	.516	.0313	4.95	.07	.17	34.0	93.1	364	1.378	816	1.178	1830	1.212	981	1.371	1888	.681	-.000	-0	-0
ERRS	.9	7.0	.025	.0002	.01	.01	.00	.1	.2	20	.013	6	.002	16	.010	5	.005	15	.013	-.000	-0	-0

FOR RUN	CRANKCASE OILS GPM	CRANKCASE OILS BTU/SEC	CRANKCASE OILS %	COOLANT SYSTEM GPM	COOLANT SYSTEM BTU/SEC	COOLANT SYSTEM %
75	5.12	1.1	2.4	11.9	7.4	15.3
76	5.20	1.0	2.1	11.9	6.9	14.4
80	5.20	1.3	2.7	11.4	6.3	12.8
79	5.34	1.5	3.0	11.6	5.5	11.3
78	5.48	2.1	4.3	11.5	5.5	11.3
77	5.41	2.4	5.1	11.5	3.4	7.1
81	5.34	2.6	5.4	12.0	4.0	8.4
82	-.00	-.0	-.0	-.0	-.0	-.0
MEAN	5.30	1.7	3.6	11.7	5.6	11.5
ERRS	.12	.6	1.2	.2	1.3	2.8

TABLE 4

EQUIVALENT AREA FOR FUEL FLOW IN INJECTOR NOZZLE VERSUS NEEDLE LIFT

(Results of Computations) (See Fig. 23)

RATE OF INJECTION = DISCHARGE COEFFICIENT * EQUIVALENT AREA * SQRT.(FUEL DENSITY * |FUEL PRESSURE - CYLINDER PRESSURE|) / 415.53855
(LBM/HOUR) SQ IN/1000000 (LBM/CUFT) (PSIA) (PSIA)

INJECTOR HAS FOUR .01181 INCH HOLES, CONTACT SURFACE HAS DIAMETERS .07320 & .13750 AND HEIGHT .05389, TIP ANGLE IS 66.50 DEGREES

EQUIVALENT AREA = 1/SQRT.(1/(OUTLET AREA FOR NEEDLE & SEAT).P.2 + 1/(AREA OF HOLES).P.2 - (DISCHARGE COEFFICIENT/AREA OF BODY).P.2)
MILS*(126.1 - .8046*MILS) 438.2 4208.4

ASSUME DISCHARGE COEFFICIENT = .7000

EQUIVALENT AREA (SQUARE INCHES/1000000) FOR EVERY .05 MIL LIFT (MIL = INCH/1000) FROM .00 TO 30.00 MILS

MILS	.00	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75	.80	.85	.90	.95	1.00
.00	.0	6.3	12.6	18.9	25.2	31.4	37.6	43.8	50.0	56.1	62.2	68.3	74.3	80.3	86.2	92.1	97.9	103.6	109.3	114.9	120.5
1.00	120.5	126.0	131.5	136.8	142.1	147.3	152.5	157.6	162.6	167.5	172.4	177.1	181.8	186.5	191.0	195.5	199.9	204.2	208.4	212.6	216.6
2.00	216.6	220.7	224.6	228.5	232.2	235.9	239.6	243.2	246.7	250.1	253.5	256.7	260.0	263.1	266.2	269.3	272.2	275.1	278.0	280.8	283.5
3.00	283.5	286.2	288.8	291.4	293.9	296.3	298.8	301.1	303.4	305.7	307.9	310.0	312.2	314.2	316.3	318.3	320.2	322.1	324.0	325.8	327.6
4.00	327.6	329.3	331.1	332.7	334.4	336.0	337.6	339.1	340.6	342.1	343.6	345.0	346.4	347.8	349.1	350.4	351.7	353.0	354.2	355.4	356.6
5.00	356.6	357.8	358.9	360.0	361.1	362.2	363.3	364.3	365.3	366.3	367.3	368.3	369.2	370.1	371.0	371.9	372.8	373.6	374.5	375.3	376.1
6.00	376.1	376.9	377.7	378.5	379.2	380.0	380.7	381.4	382.1	382.8	383.5	384.1	384.8	385.4	386.1	386.7	387.3	387.9	388.5	389.1	389.7
7.00	389.7	390.2	390.8	391.3	391.8	392.4	392.9	393.4	393.9	394.4	394.9	395.3	395.8	396.3	396.7	397.2	397.6	398.1	398.5	398.9	399.3
8.00	399.3	399.7	400.1	400.5	400.9	401.3	401.7	402.0	402.4	402.8	403.1	403.5	403.8	404.2	404.5	404.8	405.2	405.5	405.8	406.1	406.4
9.00	406.4	406.7	407.0	407.3	407.6	407.9	408.2	408.5	408.7	409.0	409.3	409.5	409.8	410.1	410.3	410.6	410.8	411.1	411.3	411.5	411.8
10.00	411.8	412.0	412.2	412.5	412.7	412.9	413.1	413.3	413.5	413.7	414.0	414.2	414.4	414.6	414.8	415.0	415.1	415.3	415.5	415.7	415.9
11.00	415.9	416.1	416.2	416.4	416.6	416.8	416.9	417.1	417.3	417.4	417.6	417.8	417.9	418.1	418.2	418.4	418.5	418.7	418.8	419.0	419.1
12.00	419.1	419.3	419.4	419.6	419.7	419.8	420.0	420.1	420.2	420.4	420.5	420.6	420.7	420.9	421.0	421.1	421.2	421.4	421.5	421.6	421.7
13.00	421.7	421.8	421.9	422.1	422.2	422.3	422.4	422.5	422.6	422.7	422.8	422.9	423.0	423.1	423.2	423.3	423.4	423.5	423.6	423.7	423.8
14.00	423.8	423.9	424.0	424.1	424.2	424.3	424.4	424.5	424.5	424.6	424.7	424.8	424.9	425.0	425.1	425.1	425.2	425.3	425.4	425.5	425.5
15.00	425.5	425.6	425.7	425.8	425.8	425.9	426.0	426.1	426.1	426.2	426.3	426.4	426.4	426.5	426.6	426.6	426.7	426.8	426.8	426.9	427.0
16.00	427.0	427.0	427.1	427.2	427.2	427.3	427.4	427.4	427.5	427.5	427.6	427.7	427.7	427.8	427.8	427.9	428.0	428.0	428.1	428.1	428.2
17.00	428.2	428.2	428.3	428.3	428.4	428.5	428.5	428.6	428.6	428.7	428.7	428.8	428.8	428.9	428.9	429.0	429.0	429.1	429.1	429.2	429.2
18.00	429.2	429.3	429.3	429.3	429.4	429.4	429.5	429.5	429.6	429.6	429.7	429.7	429.8	429.8	429.8	429.9	429.9	430.0	430.0	430.0	430.1
19.00	430.1	430.1	430.2	430.2	430.2	430.3	430.3	430.4	430.4	430.4	430.5	430.5	430.6	430.6	430.6	430.7	430.7	430.7	430.8	430.8	430.8
20.00	430.8	430.9	430.9	430.9	431.0	431.0	431.1	431.1	431.1	431.2	431.2	431.2	431.2	431.3	431.3	431.3	431.4	431.4	431.4	431.5	431.5
21.00	431.5	431.5	431.6	431.6	431.6	431.7	431.7	431.7	431.7	431.8	431.8	431.8	431.9	431.9	431.9	431.9	432.0	432.0	432.0	432.1	432.1
22.00	432.1	432.1	432.1	432.2	432.2	432.2	432.2	432.3	432.3	432.3	432.3	432.4	432.4	432.4	432.4	432.5	432.5	432.5	432.5	432.6	432.6
23.00	432.6	432.6	432.6	432.7	432.7	432.7	432.7	432.7	432.8	432.8	432.8	432.8	432.9	432.9	432.9	432.9	432.9	433.0	433.0	433.0	433.0
24.00	433.0	433.1	433.1	433.1	433.1	433.1	433.2	433.2	433.2	433.2	433.2	433.3	433.3	433.3	433.3	433.3	433.4	433.4	433.4	433.4	433.4
25.00	433.4	433.4	433.5	433.5	433.5	433.5	433.5	433.6	433.6	433.6	433.6	433.6	433.6	433.7	433.7	433.7	433.7	433.7	433.8	433.8	433.8
26.00	433.8	433.8	433.8	433.8	433.9	433.9	433.9	433.9	433.9	433.9	433.9	434.0	434.0	434.0	434.0	434.0	434.0	434.1	434.1	434.1	434.1
27.00	434.1	434.1	434.1	434.1	434.2	434.2	434.2	434.2	434.2	434.2	434.3	434.3	434.3	434.3	434.3	434.3	434.3	434.4	434.4	434.4	434.4
28.00	434.4	434.4	434.4	434.4	434.4	434.5	434.5	434.5	434.5	434.5	434.5	434.5	434.5	434.6	434.6	434.6	434.6	434.6	434.6	434.6	434.7
29.00	434.7	434.7	434.7	434.7	434.7	434.7	434.7	434.7	434.7	434.8	434.8	434.8	434.8	434.8	434.8	434.8	434.8	434.9	434.9	434.9	434.9

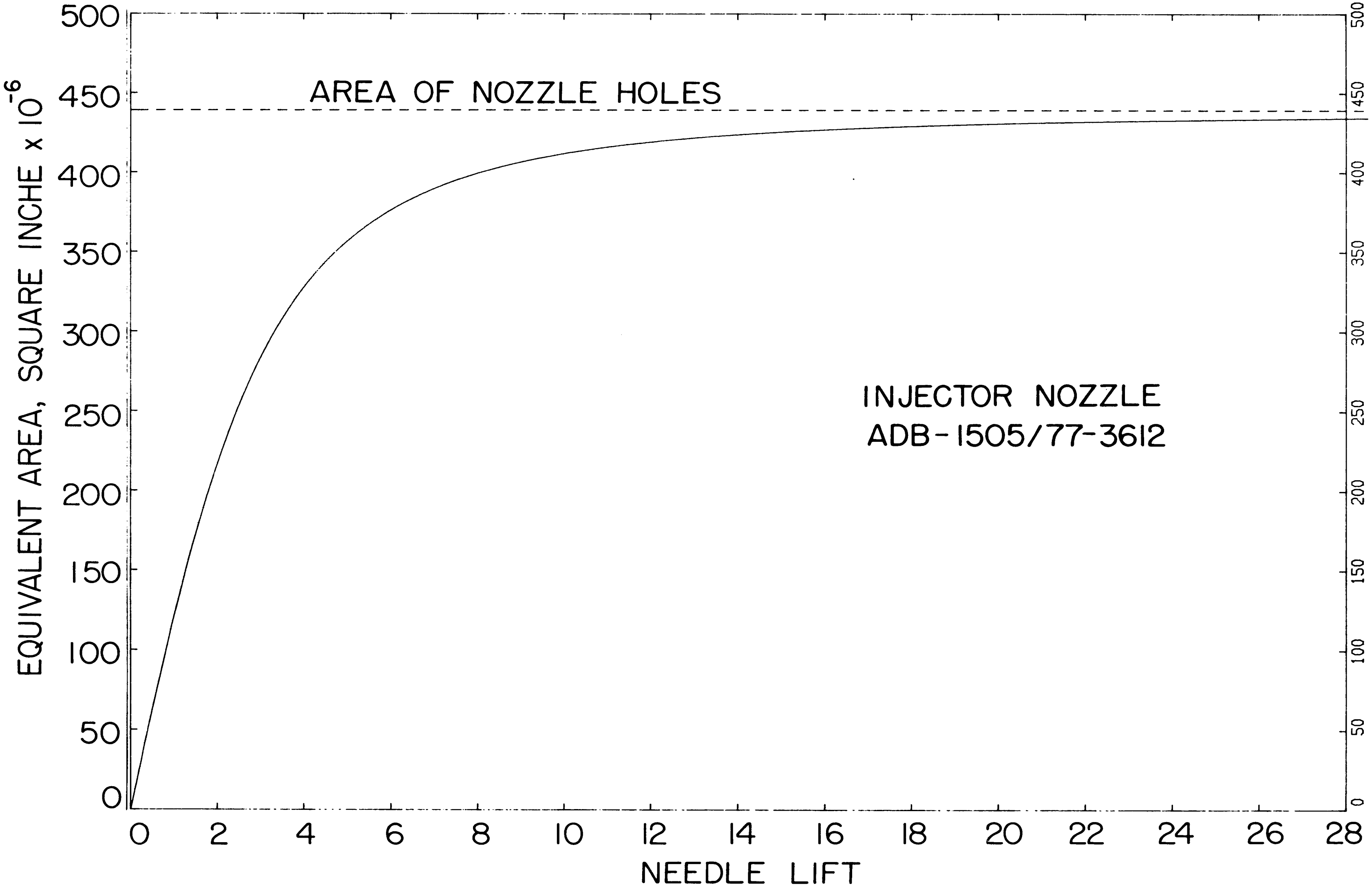


Fig. 23. Equivalent area for fuel flow in injector nozzle versus needle lift.

APPENDIX C

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