DESIGN AND TESTING OF A MICROCOMPUTER AIR-FUEL RATIO, IGNITION TIMING SYSTEM, FOR AN ELECTRONICALLY FUEL INJECTED INTERNAL COMBUSTION ENGINE

by

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CHAPTER I

INTRODUCTION

1-1 Introduction

Up through the 1960's internal combustion engine control was relatively simple. The average automobile user wanted an engine that performed adequately and reliably, but no one was thinking about emissions and very little thought was given to fuel economy. In recent years, pollution has become a major societal problem and emission control has become a major concern of the automobile industry.

With the advent of fuel shortages and rapidly rising fuel prices the automotive industry now faces the problem of maximizing fuel economy and continuing to decrease exhaust emission levels without sacrificing performance. The basic difficulty is that engine changes which increase fuel economy usually increase emission levels while changes which reduce emission levels usually also reduces fuel economy.

The advent of governmental emission standards in 1968 resulted in the requirement that the automobile engine have more precision in metering and mixing the fuel and air to maintain an air-fuel ratio that would reduce exhaust emissions. Also required is accuracy in the exact firing time of ignition systems. This precision is also an important requirement in terms of driveability and economy.

Emission legislation will impose HC/CO/NO_x limits of 1.5/15/2.0 grams per mile by 1977 and 0.41/3.43/1.0 grams per mile by 1981-82 (1). Over the past four years, because of the national fuel shortage there has been an immediate demand for more efficient fuel consumption. Fuel economy legislation requires an average 18 miles per gallon by 1978 and 27.5 miles per gallon by 1985.

Clearly more accurate controls will be necessary to achieve these requirements. There are essentially three basic control functions for the internal combustion engine: Air-fuel ratio, spark advance and exhaust gas recirculation. Spark advance is dependent on exhaust gas recirculation and the air-fuel ratio, and exhaust gas recirculation level is dependent on the air-fuel ratio. Therefore, control of the air-fuel ratio can be the fundamental variable (2).

In order to achieve these goals extremely accurate control will be necessary. The most promising method that can provide this high degree of accuracy in sensing, computation, and control, is electronics. It has been almost 30 years since the world's first electronic digital computer was built. The increase in usage of the digital computer has had an important impact on the field of engineering. The latest computer revolution has been the result of the large scale integration of thousands of electronic elements in a single device. The microprocessor or microcomputer which was invented seven years ago is now finding applications in a wide variety of systems. Since 1971, when the first mocroprocessors were introduced, the automotive engineer has increasingly been challenged to utilize these software programmable devices in new automotive electronic systems.

The extensive computational and logic capability and the versatility of the microprocessor make it ideally suited for an automotive control application. The highly cost-conscious automotive industry is beginning to conclude that, with mass production, the microprocessor's cost-effectiveness will have a tremendous impact on the design, performance, and overall driveability of automobiles in the years to come.

This thesis describes work in a continuing research project in the Mechanical Engineering Department at Kansas State University in microcomputer engine control. In the previous research (3), air-fuel ratio and engine speed controllers were designed and tested. The controllers were based on a table look-up algorithm to determine control variables. The objective of this thesis is to implement an air-fuel ratio (A/F) controller based on a computational algorithm and a spark timing controller.

The remainder of this chapter will include a discussion of the objectives of this work and a literature review on electronic engine control by microprocessor.

1-2 Objective of the Work

The objective of this project is that spark timing and air-fuel ratio be simultaneously controlled by the microcomputer in such a manner that the desired engine performance is always achieved. The scope of this research was limited to testing engine speeds between 1000 and 3000 rpm following engine warm-up and engine loads between 10 and 40 lb. ft. The microcomputer was programmed to control spark timing as well as spark advance in addition to fuel injection to obtain three prescribed air-fuel ratios: 14-1, 16-1, and 18-1.

The base goal of this research was to investigate problems associated with the implementation of a microcomputer used as a real-time controller of an electronically fuel injected internal combustion engine. Both the air-fuel ratio and the spark timing were implemented on a single microcomputer and both were open loop systems.

The microcomputer used as the controller for this research was a KIM-1 microcomputer system, manufactured by MOS Technology, Inc. The complete discussion of this device will be presented in section 2-3, and the specifications for this microcomputer are given in Appendix A.

The internal combustion engine used for this research was a 1968 Volkswagen engine which was electronically fuel injected. The gasoline injection system for this engine was equipped with a Bosch system and electromagnatically actuated injection valves and solid state circuitry for the metering of injected fuel volume. The complete description of the engine will be given in section 2-3 of chapter 2, and detailed specifications of this engine are listed in Appendix B.

1-3 Literature Review - Electronic Engine Control by Microprocessor

The use of a microprocessor to control a production automotive engine has become very important to the major automobile manufacturers in the United States. General Motors has had an extensive research program in which several in-vehicle experimental, integrated, automotive electronic systems have been studied and built. Six electronics engineers from GM research laboratories have taken steps to investigate microcomputer engine controls (4). Focusing on the economy-emmissions effects of varying spark advance, air-fuel ratio and exhaust gas recirculation, the team devised a ratio of complementary packages for developing systems to control these engine variables.

One of these packages was the complete test-cell "mapping" of a 5.7-litter (350 cubic-inch) V-8 gasoline engine (5). Mapping is the thorough documentation of how engine fuel consumption and emission levels respond to changes in spark advance, air-fuel ratio, and exhaust gas recirculation over the operating speed and load range. General Motors applied MOS/LSI technology in the design of this automotive computer. It used a single-chip, 4-bit parallel microprocessor with subsystems for both digital display and control functions, which included: ignition timing, ignition dwell, anti-theft, engine speed, four-wheel lock control, speed limiting, speedometer, time of day, speed warning, and traction control. Interface circuitry handled the asynchronous load associated with the vehicle operation and calculation, display, logic, and control were handled by the microprocessor.

Ford Motor Company has signed an agreement with Toshiba for a 12-bit device to control the spark ignition timing and exhaust gas recirculation mass flow based on a number of engine variables. Input-output data and intermediate results are stored in a 128 word, read-write memory. The software program to control the engine is stored in 1500, 12-bit words of Read Only Mercury. The system includes an 8-bit analog-to-digital converter with an eight channel analog multiplexer under CPU control (6). Ford plans to install their first microprocessor on a limited number of 1978 model cars.

The Chrysler Corporation plans to have a microprocessor operating on one of their 1980 model cars. They have contracts with RCA for an 8-bit C/MOS microprocessor and with Texas Instruments for a 16-bit N/MOS microprocessor (7). Chrysler has indicated that the use of the microprocessor will be for engine control.

An electronic spark timing system with a 10-bit custom made microprocessor by Rockwell International is the first use of a microprocessor on a production automobile. This system is designed for the 1977 Oldsmobile Toronado (7). The appropriate spark time is computed by the MPU, based on environmental and engine operational information such as engine coolant temperature, manifold vacuum, crankshaft position, and engine speed.

CHAPTER II

THE AIR-FUEL RATIO CONTROLLER

2-1 Introduction

An air-fuel ratio controller has been developed, implemented, and tested which computes the amount of fuel necessary for operating the engine based on the requirements of the engine such as speed and load. The air-fuel ratio controller maintains the fuel flow in accordance with measured air flow and prescribed air-fuel ratio.

2-2 Literature Review-electronic Air-Fuel Ratio Control in Automobiles

For more than ten years automotive and related research organizations have been studying the relationship between exhaust emission and fuel economy. One of the objectives of automotive engineers is to obtain lower emissions with a minimum penalty on fuel economy. One approach to improve present engine performance is by better control of air-fuel ratio.

Conventional carbureted engines that mix fuel and air have been greatly improved in recent years. Even with the improvements this system still does not give an accurate air-fuel ratio over the range of operating conditions encountered. A more accurate method of metering fuel is the electronic fuel injection system. The basic patents on electronic fuel injectors were granted in 1961 to the Bendix Corporation (8). Robert Bosch Gmbtl of West Germany was licensed by Bendix Corp. to develop an electronic fuel injection system for a small displacement, four cylinder engine used in European Automobiles. This system improved the horsepower output of these engines by about five percent.

In 1967 the Bosch D-Jetronic fuel injection system was available as optional equipment on the 1.6 liter displacement, four cylinder Volkswagen engine. The fuel injection duration is regulated as a function of the engine speed and the absolute manifold pressure. Fuel was injected into the intake manifold near the intake valves.

The electronic fuel injection program by the Bendix Corporation was restarted during 1970. They used the work done by Bosch on the D-Jetronic System (10) as the basis for a new system called the L-Jetronic.

There were three main improvements in this new system. First, to improve performance, an air flow sensor was developed to replace the manifold pressure sensor; second, to reduce cost and increase reliability, integrated circuits were used in the elctronic control unit; and finally, to simplify the system, a single channel fuel distribution system was used. On this system the injectors are connected in parallel and operated two times for every camshaft revolution. The inputs to this system are engine speed and air flow rate from the air mass flow sensor which was developed by Robert Bosch. This sensor consists of a plate that turns in a rectangular shaped duct in response to tye air flow pressure acting against a spring. A potentiometer connected to the plate generates a voltage proportional to the air mass flow rate. The L-Jetronic system has been in use since 1973 (11).

The Bosch Corporation recently completed development of a new electronic control system (12). This system provides a better solution to some of the auto industry's new demands, such as higher safety standards, lower emission of pollutants, lower fuel consumption, better driveability, and higher reliability. They report that in the near future additional electronic systems will control other parts of the automobile. These systems include ignition control, fuel injection, automatic transmission control, anti-skid control, and maintenance monitoring.

The new Bosch injection control system includes a new electronic control unit and several new sensors to sense speed, temperature, and air flow. The control unit for this system is an NMOS microprocessor system. The speed sensor is different from what was previously developed.

In this system the sensor was mounted on the crankshaft and contains a number of segments corresponding to half the number of cylinders. The segments are staked out by two magnets of inverse polarity, one at the beginning and the other at the end of the segment. The time which the segment takes to pass a pick up may be counted in order to get a number inversly proportional to engine speed. The mass air flow sensor is the same as the old system. Also with this system another sensor is installed to measure the intake manifold pressure. A pressure box shifts the core of a coil changing the inductance of the coil. The variable inductance changes the oscillating frequency of an operational amplifier circuit. The oscillations are counted to produce a digital value proportional to the manifold pressure.

An air-fuel ratio control using a simple microprocessor was of interest to the Essex Group of United Technology (2). They have completed an open loop control system. In their research air mass flow and engine speed were used as the two main inputs to the digital computer. The vehicle used was a Lincoln Mark IV with a 460 CID V8 engine. Bosch injectors were used for the fuel injection system. An autotronics model 460 F was used as an air flow sensor. This is a vane type sensor with a high response rate for automotive applications. Experimental data in the vehicle was obtained for this control system utilizing the direct measurement of the intake air mass. It was felt that for the variability of speed experienced in operating conditions the density type of control would not achieve such good results as the direct measurement system.

Bendix Corporation is developing closed-loop electronic fuel injection, using an oxygen sensors which was developed by Bosch (13). The feedback element is a zirconium-dioxide oxygen sensor which measures the free oxygen in the exhaust. The voltage characteristic of the oxygen sensor is very nearly a step type, with a stable operating point around 360 mv which corresponds to a chosen air-fuel ratio. Through the utilization of the oxygen sensor and the closed loop concept it is possible to achieve a very accurate air-fuel ratio and to maintain it independent of changes and drifts in the engine and fuel preparation system. Bendix is also adding the closed loop concept to its original system which uses absolute manifold pressure and engine speed as the two main inputs. These systems are not available in production automobiles since they are still in the research and testing stage.

2-3 Physical Discription of Control System

The air-fuel ratio controller developed in this research was an open-loop system. Open-loop control systems are systems in which the control action is independent of out put. That is, the out put is neither measured nor fed back for comparison with the input. Open loop control system must be carefully calibrated and must maintain that calibration, in order to achieve the desired accuracy.

Closed loop control systems have an advantage over open loop control systems (14). The use of feed-back makes the system response relatively insensitive to external disturbances and internal variations in system parameters. It is thus possible to use relatively inaccurate and inexpensive components and obtain accurate control. From the point of view of stability open-loop control systems are easier to build, since stability is not a major problem. Stability is a major concern in the design of closed loop control systems.

The main reason for choosing an open loop control system in this research was due to lack of an appropriate feed-back element suitable for use as an exhaust gas sensor. Zirconium-dioxide oxygen sensors are being tested for this purpose by the Bendix Corporation, but one could not be obtained for this work.

Figure 1 shows the block diagram of the open loop air-fuel ratio control system. The system consist of a speed sonsor, an air flow sensor, a micro-computer, fuel injector, and the engine. The remainder of this section will provide a discussion of each part of the system.

The engine used in this research was a 1968 four cylinder, horizontally opposed, air cooled Volkswagen engine. Detailed specifications for the engine are given in Appendix B . The engine was equipped with the Bosch D-Jetronic fuel injection system (15). In this system gasoline is injected onto the heads of the intake valves by electromagnetically actuated nozzle valves. Gasoline is supplied to the injectors by a low-pressure, common rail system. Figure 2 shows the primary fuel systems; the positive displacement electric pump draws gasoline from the storage tank and delivered it to the injectors at a constant pressure of 28 psig. The constant pressure is maintained by the pressure regulating valve located at the end of the system. The excess gasoline is returned to the storage tank. The supply pressure of 28 psig was chosen by optimizing the desired degree of mixture control accuracy. At this pressure electric power consumption could be held within reasonable limits of approximately 25 watts for a medium-size engine (16).

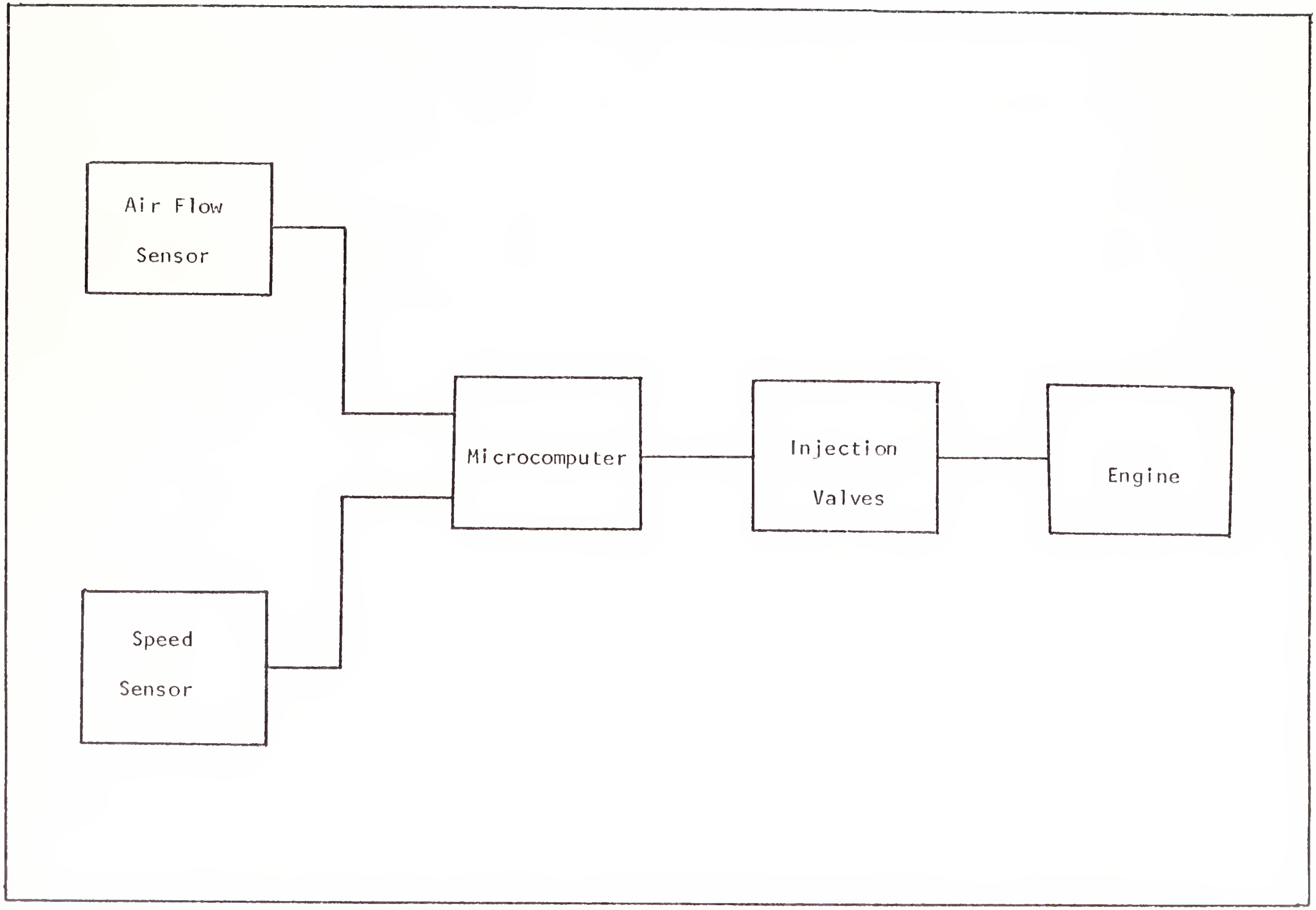


Figure 1. Air-Fuel Ratio Control System

There are four injectors in this system, one mounted over each intake valve. The injector valves are elctromagnetically actuated and serve to both meter and to atomize the fuel. The valve body contains a solenoid whose plunger is attached to the needle valve. As shown in Figure 3, a helical spring keeps the valve closed as long as the solenoid is de-energized. The fuel injectors are opened electrically in two pairs (injector pair I = cylinders 1 and 4; Injector pair II = cylinders 2 and 3). The magnetic field in the injector winding is generated by electrical pulses transmitted by the microcomputer and amplified by power transistors.

Both fuel injectors of one pair inject fuel at the same time (15). The injectors for cylinders 1 and 3 inject fuel through the open intake valves stroke, while the injectors of cylinders 2 and 4 inject onto the still closed intake valves while the exhaust gases are being forced out. In this case the fuel is stored in the manifold of the intake valves until the next intake stroke. Figure 4 shows the start of the injection pulses of the two groups of injectors relative to spark timing and intake stroke. The injector valve lift is approximatley .006", and its response time is about 1 ms. The open period of the injectors may range from 2 to 10 ms. depending on the amount of fuel required.

The opening pulse for each group of injector valves is initiated by a trigger contact arrangement installed within the distributor. Each set of contacts generates a pulse for its injectors once for every revolution of the camshaft. The two contracts are spaced 180 camshaft degrees apart. Alternately closing a signal-lobe cam on the distributor shaft generates a square-wave signal exactly synchronized with engine speed (16). The two distributor signals are used to determine the starting of the injection pulses as well as

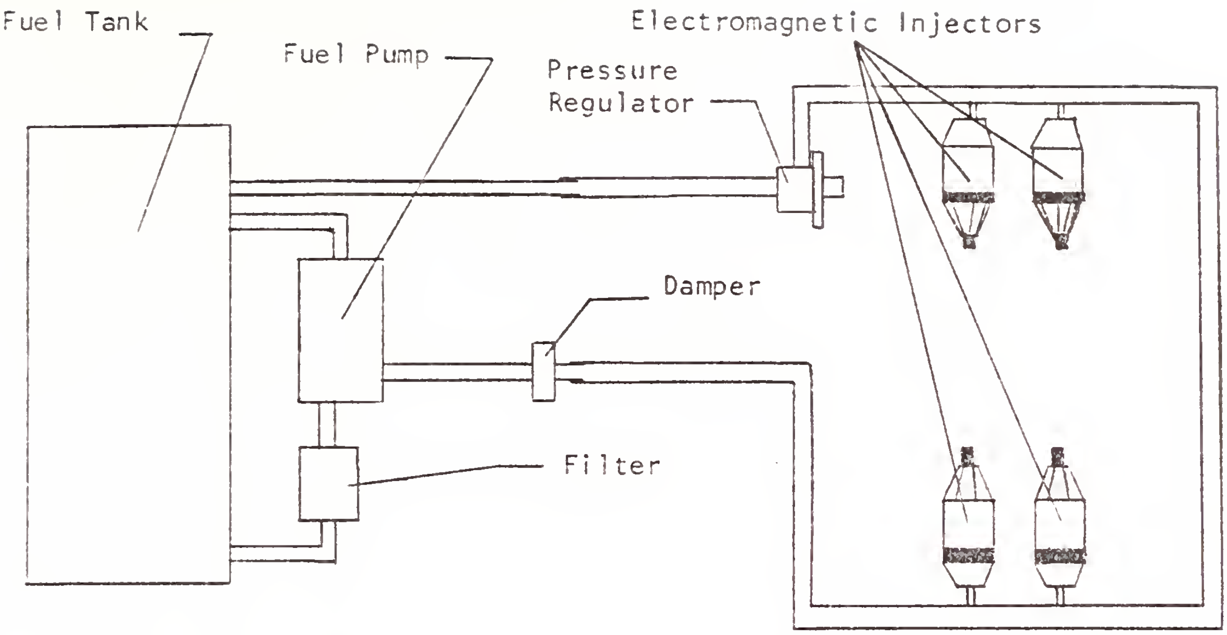


Figure 2. Primary Fuel Supply System

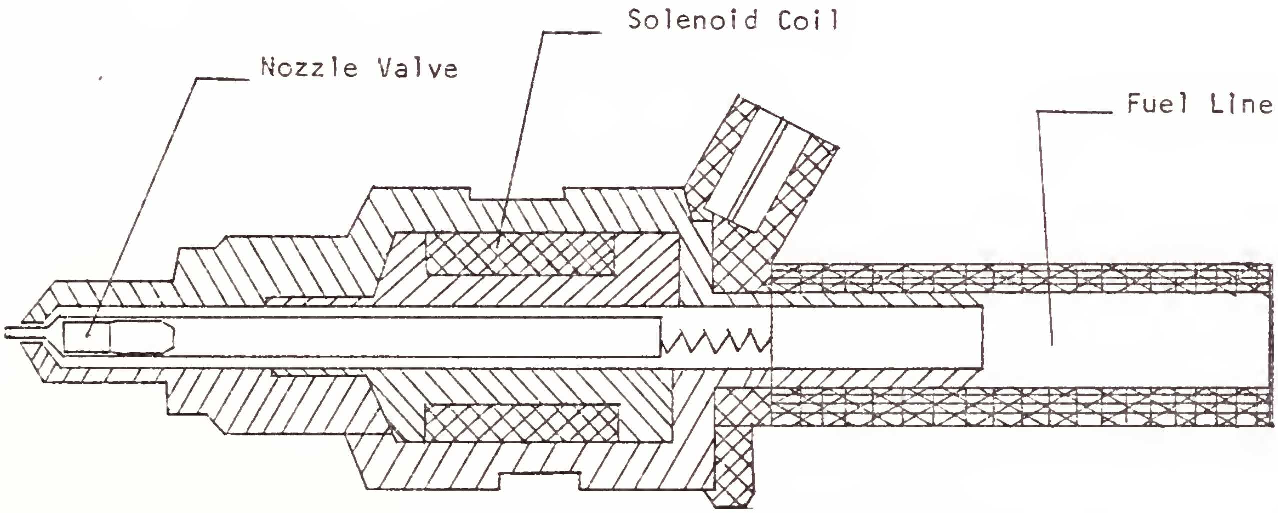


Figure 3. Electromagnetic Fuel Injector

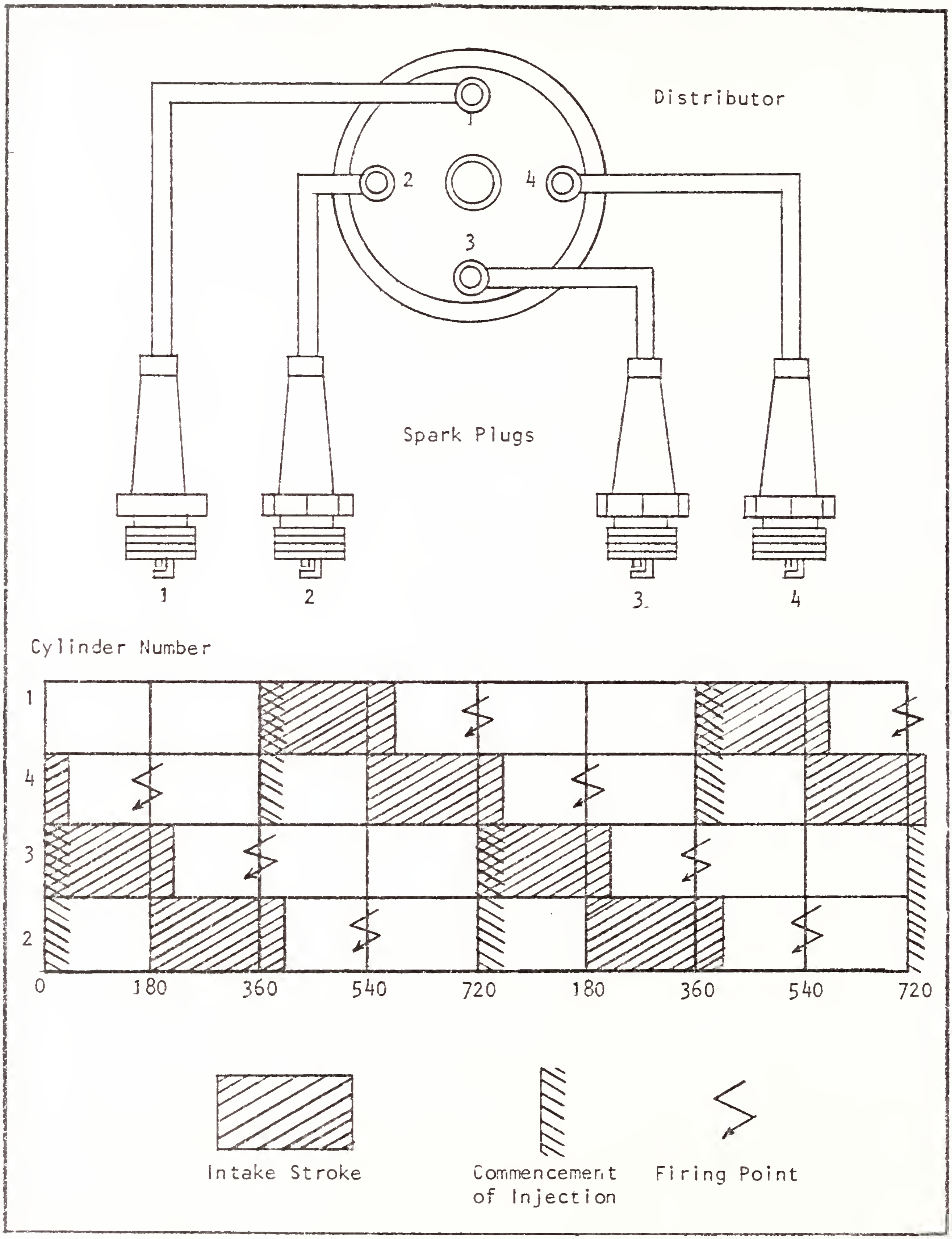


Figure 4. Start of fuel Injection Verses Intake Stroke and Firing Point

to measure the engine speed. The injection time is computed by the micro-computer based on the engine speed, air mass flow rate, and specified air-fuel ratio.

The engine speed is measured by the electronic speed sensor shown in Figure 5. The desire specifications for this sensor were that it:

a. be accurate to 0.5% over speed range of 600 to 3600 rpm,

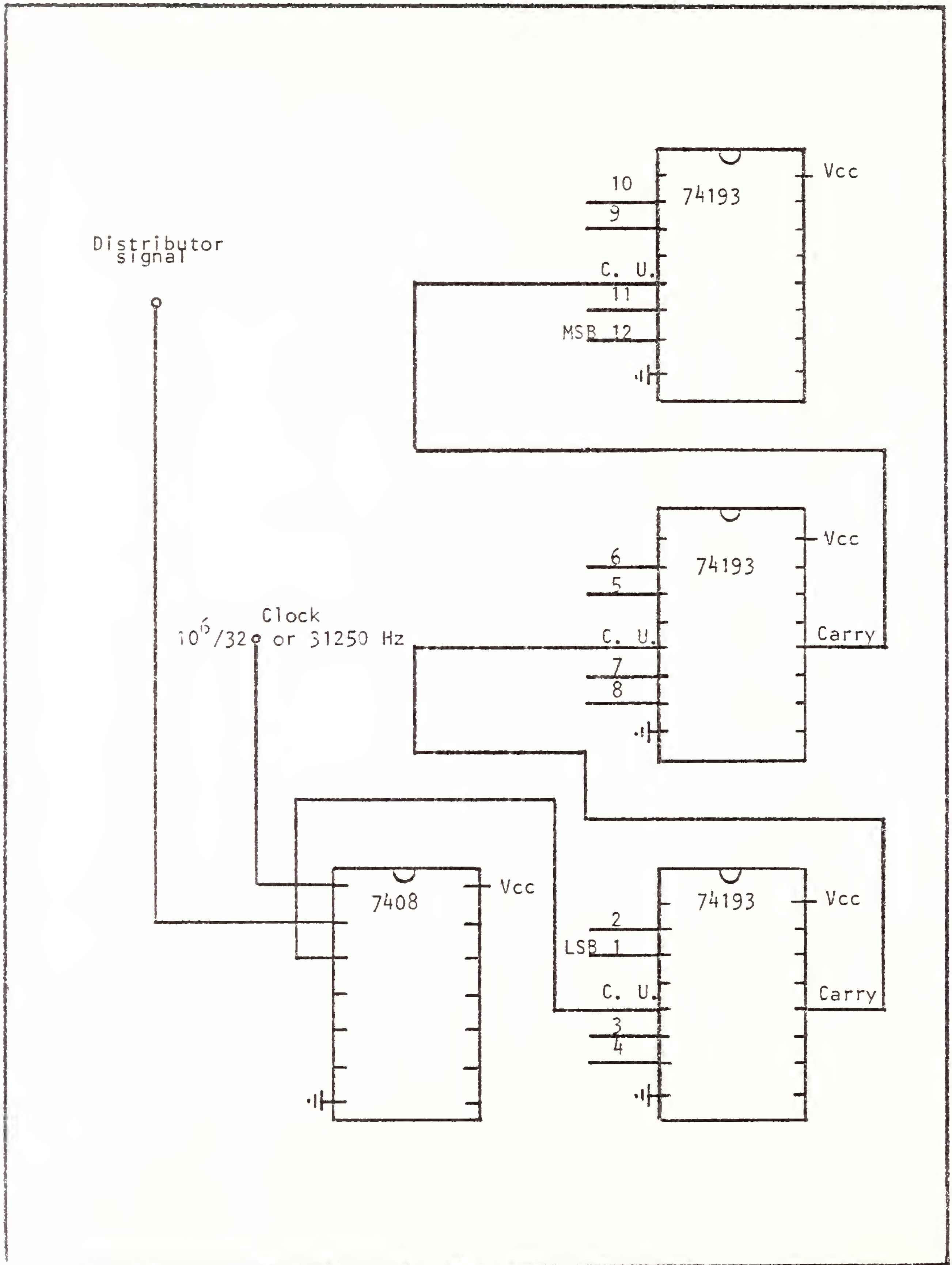
b. be compatable with the microcomputer input/output port,

c. produce a value inversely proportional to engine speed, and

d. be constructed of readily available, inexpensive components.

To obtain these requirements a counting circuit was designed using TTL integrated circuits. The distributor signal, a square wave synchronized with the engine at a frequency of one half the engine speed, is used to gate a high frequency clock signal into the counter circuit. Some signal conditioning was necessary to clear up the distributor signal, as shown in Figure 6. The microcomputer clock which operates at 1 megahertz was divided by 32 using 2 TTL counters and used as the clock input to the counters of the speed sensor.

The speed sensor is designed so that the clock signal is gated to the counting network only while the distributor pulse is at the high level. The counting network is read into the microcomputer and reset during the low level portion of the distributor signal cycle. The use of 3, 4-bit binary counters produces a 12-bit value which is inversely proportional to the engine speed. The sensor will produce a count of 520 at 3600 rpm and 3125 at 600 rpm. The minimum speed for which the sensor will function is 460 rpm (count of 4096). The resolution of the sensor at 3600 rpm is 0.2%. The maximum speed for which the resolution will be less than 0.5% is 9300 rpm which is far beyond the rated speed of the engine.



Figur 5. Speed Sensor

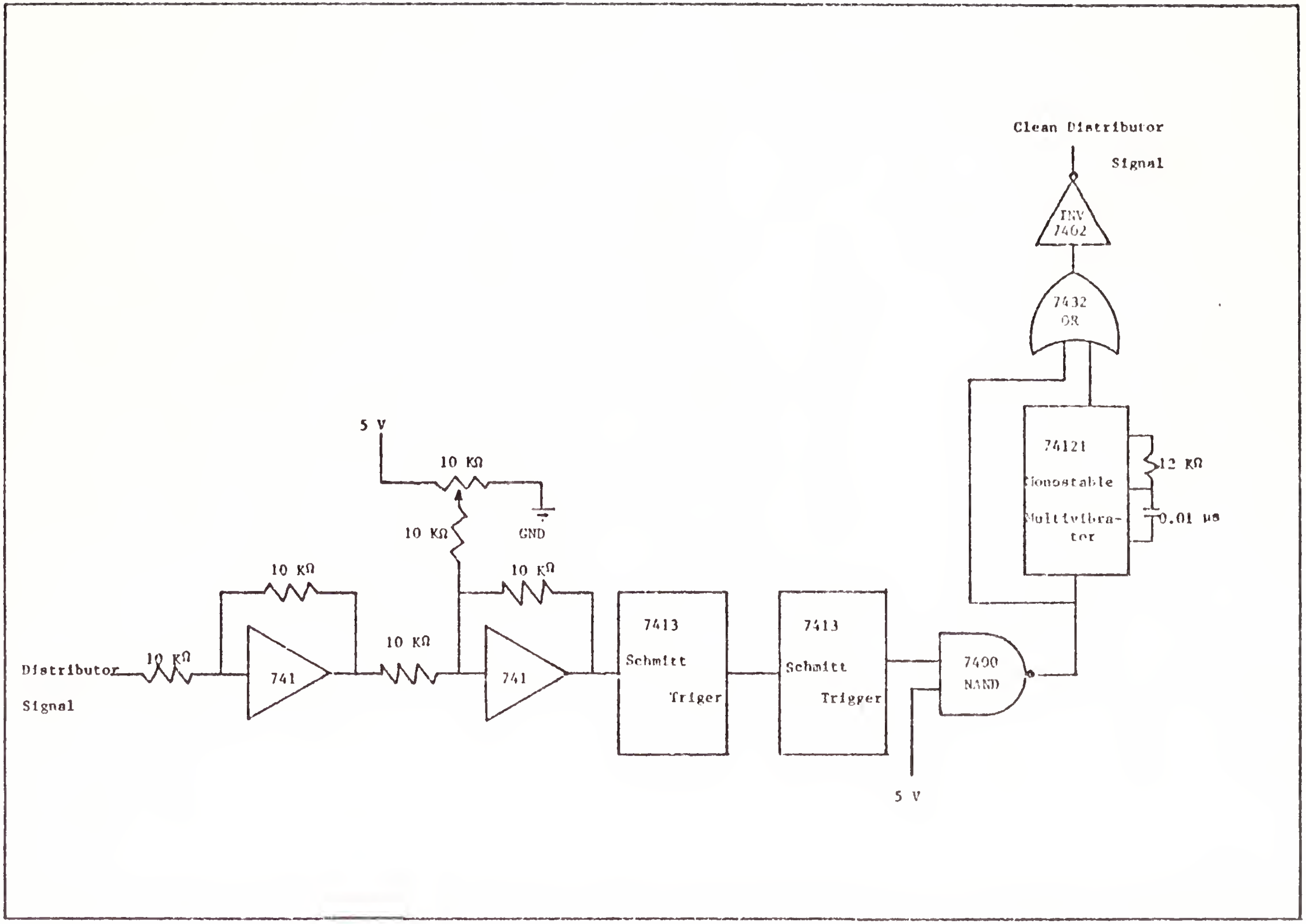


Figure 6. TTL Circuit Diagram to Clean The Distributor Signal

The fuel acquired for proper operation of the engine is a function not only of the speed but also of the load. The load may be implied by sensing the intake manifold pressure or the intake air-flow rate. In this project we are using the intake air-flow, since this is a better indication of load than manifold pressure. As shown in Figure 7 the intake air flow sensor is installed in front of the throttle. Figure 8 shows a sectional view of the air flow sensor which was developed by Robert Bosch (12). This sensor is a rectangular shaped channel in which air flow pressure forces a plate to turn inside the channel against a spring. To achieve a constant relative measuring error over the span of the sensor, the relationship between the angular position and the air flow quantity is designed to be logarithmic. An analog voltage signal proportional to the air flow quanity is generated by a special potentiometer which is connected to the plate. This analog voltage value needs to be converted to a digital value to be used by the microcomputer. An analog-to-digital converter model ADC-10Z by Analog Devices, Inc., was used for this purpose. This is a 10-bit converter with a maximum relative accuracy of 1 1/2 LSB, ($\pm$ 0.05% of span) and a conversion time is 20 usec. The output voltage of the air-fuel sensor ranged between 0 to 8V and a 0 to 10 volt range was used on the analog-to-digital convertor.

A KIM-1 microcomputer manufactured by Mos Technology Inc. was used for the controller for this project. The specifications for KIM-1 are given in Appendix A . Digital values representing the air flow and engine speed were read by the microcomputer once in each engine cycle. These values were scaled by the microcomputer to represent exact value for the air flow and the inverse of the engine rpm. They were then used to compute the required fuel injection time to produce the desired air fuel ratio.

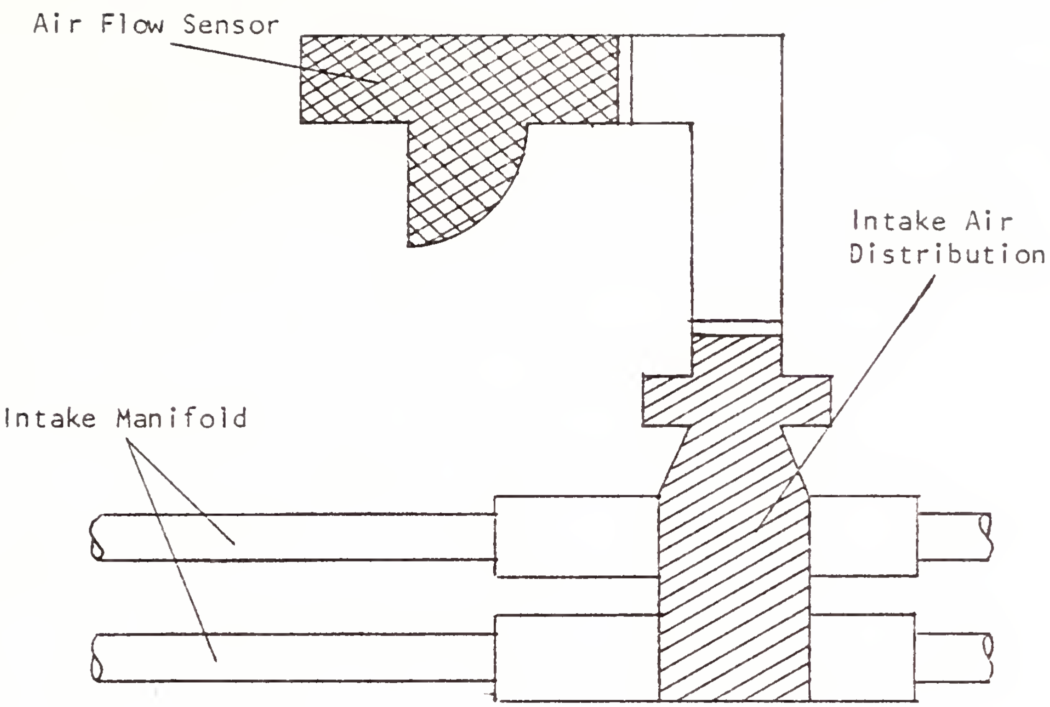


Figure 7. Intake Air Flow System

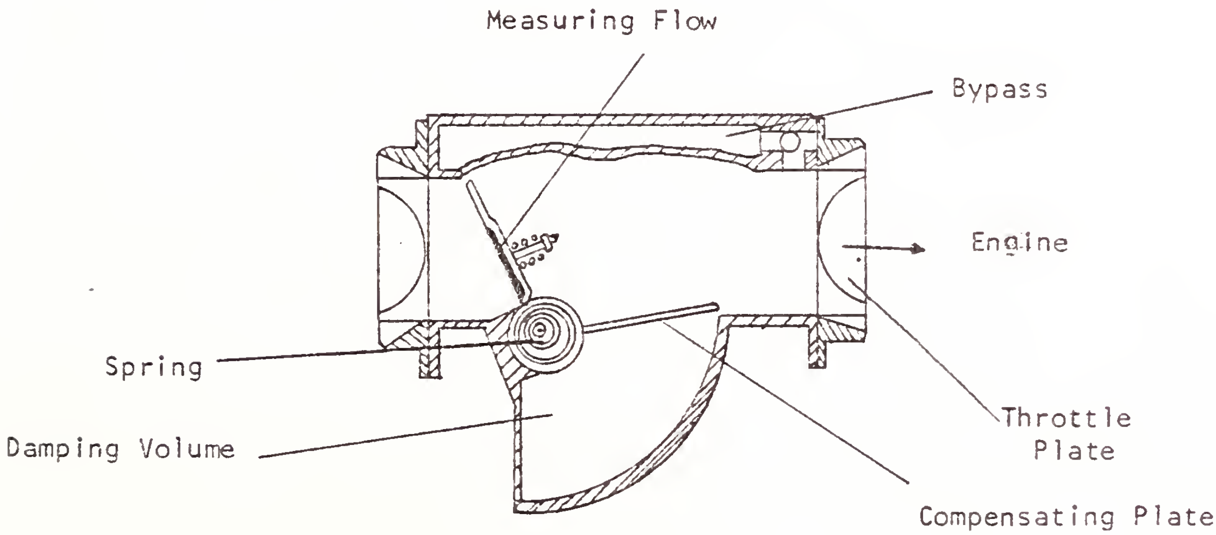


Figure 8. Sectional View of the Airflow Sensor

2-4 Development of Mathematical Model of the Control System

Implementation of a real-time control strategy using a microprocessor requires the development of the mathematical relationships between the conditions of the engine and the control signal. The mass of the fuel injected in each cycle is the control variable for the electronic fuel injection system. This variable is a function of the time duration of injector opening. The control algorithm is the mathematical relationship between the engine parameters and the time duration of injection.

The relation for the time duration of injection was drived (3) for a single engine cycle as follow:

$$t = K_t \, K_{f/a} \, M_\alpha \qquad \text{equ. 1}$$

where

$$M_\alpha = \frac{m_\alpha}{2N} \qquad \text{equ. 2}$$

and where:

t = duration of time for which the injector is open in milliseconds (ms).

K_t = convertion factor in which mass of fuel injected (lb_m) per cycle is converted into time duration of injection in milisecond (ms).

$K_{f/a}$ = fuel to air ratio.

M_α = mass of air injected per engine revolution into each cylinder of the four cylinder engine in pound mass (lb_m).

m_α = mass air flow rate in pound mass per minute (lbm/min)

N = engine speed, rpm.

The mass air flow rate, m_α, was measured by air flow sensor. A calibration was required for this sensor in order to obtain an exact value of mass air flow. The output of the air flow sensor was an analog voltage which was converted to a digital value by an analog to digital convertor. The digital value was converted to air flow value by using the calibration relationship. Figure 9 shows graphically the calibration of air mass flow rate versus the air flow sensor voltage.

The mathematical equations used by the microprocessor to convert the air flow sensor voltage to the air mass flow rate was the least-square fit of the Piecewise Linear model shown in Figure 10. The mathematical relationships are given in Table 1.

$$m = 0.355\ V \quad \text{for} \quad 0 \leq V < 2.0 \ \text{volts}$$

$$m = 0.41\ V - 0.14 \quad \text{for} \quad 2.0 \leq V < 4.0 \ \text{volts}$$

$$m = 0.32\ V + 0.22 \quad \text{for} \quad 4.0 \leq V < 5.0 \ \text{volts}$$

$$m = 1.08\ V - 3.58 \quad \text{for} \quad 5.0 \leq V < 6.5 \ \text{volts}$$

Table 1. Piecewise linear model of air mass flow rate as a function of air flow sensor voltage.

The speed of the engine was measured by the speed sensor. Calibration of this sensor results the following relationship:

$$N = \frac{f(60)}{\text{count}} \qquad \text{equ. 3}$$

where

f = frequency of clock in cycle per second (10 /32 = 31,250 hz)

count = value read by the speed sensor

60 = convertion from seconds to minutes.

The value of count was read by the microprocessor each engine cycle and is multiplied by the value 1/120F to produce the value 1/2N.

To determine the value of K_t a third calibration was required. This calibration was obtained by measuring the mass of fuel consumed by the engine over a measured length of time. Figure 11 shows the result of this calibration. Each point on the curve represent the average of five tests made at a certain speed and load. The result of a best fit relationship based on

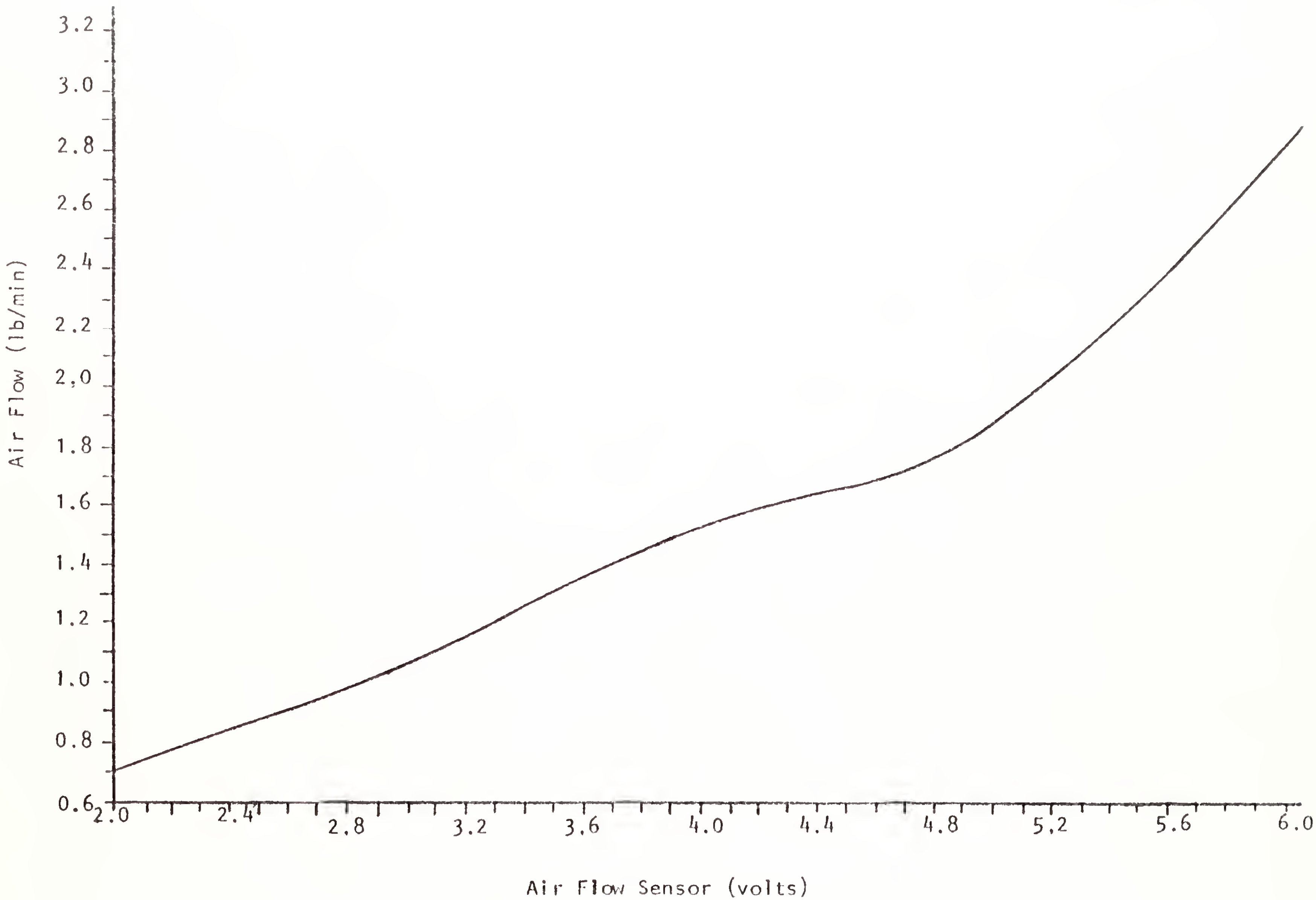


Figure 9. Air Flow Sensor Calibration

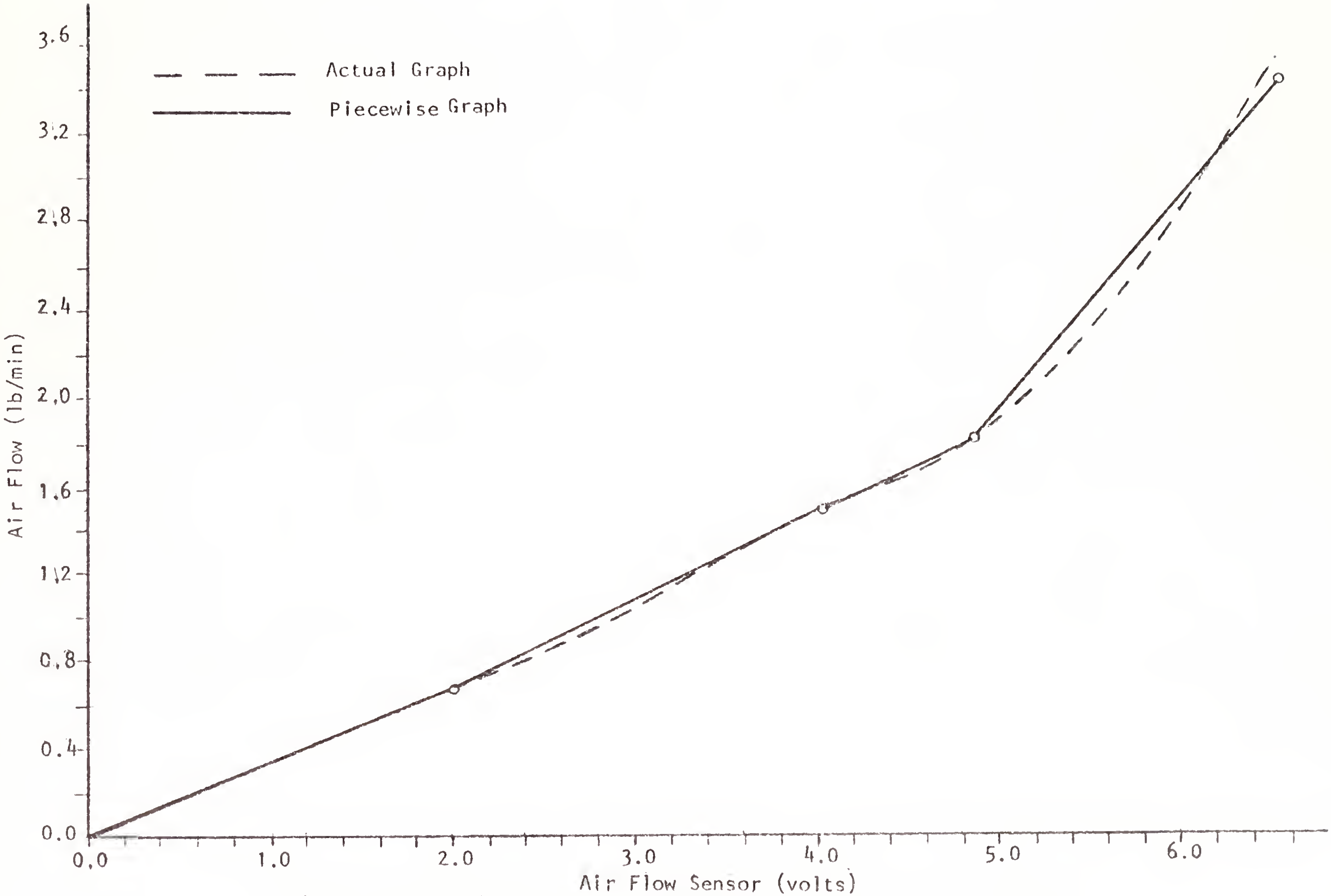


Figure 10. Piecewise Linear Best Fitted Graph for Air Flow Sensor

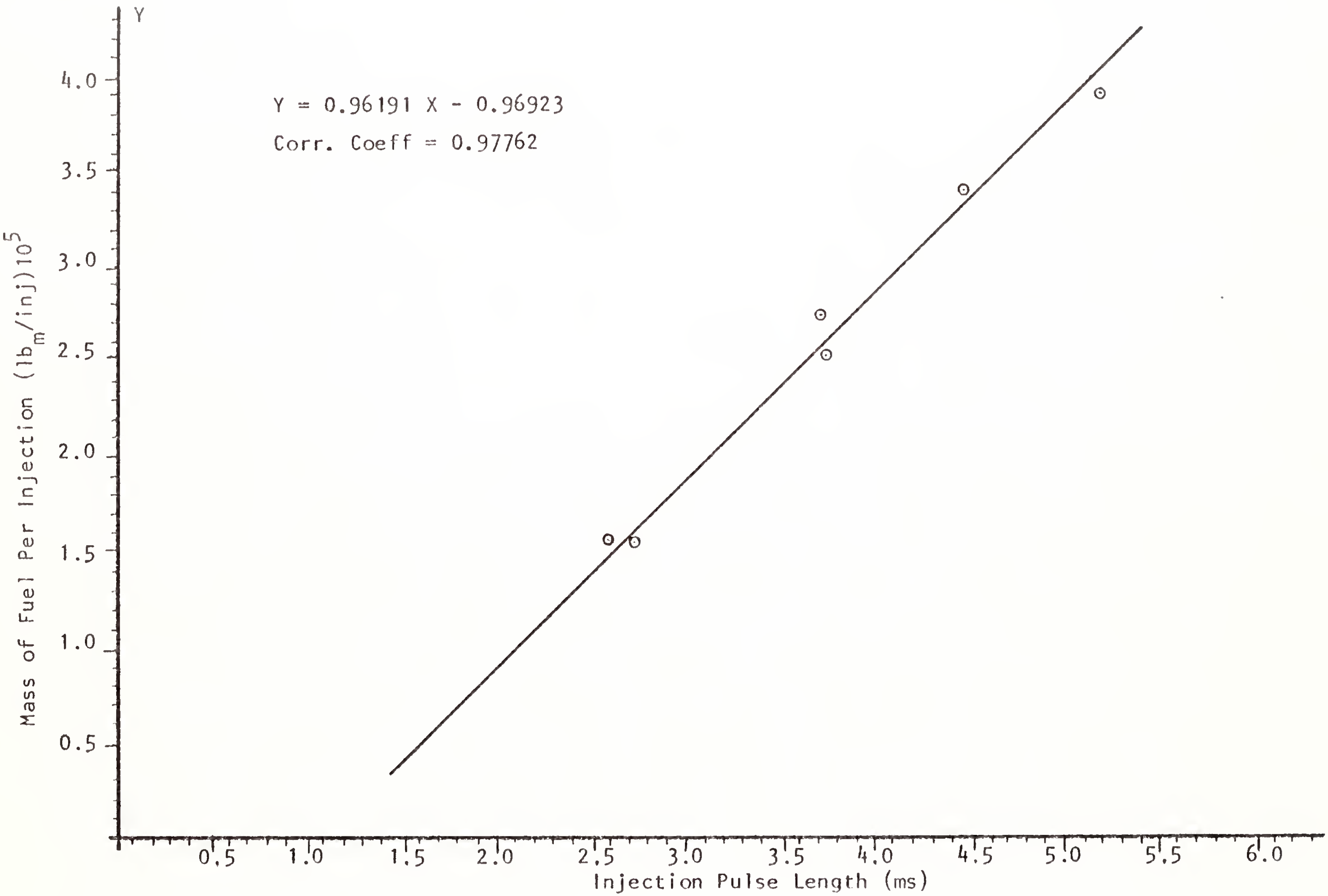


Figure 11. Fuel Injection Calibration

least-squares regression routine is:

$$t = \frac{M_f + 0.96923}{0.96191} \qquad \text{equ. 4}$$

where:

M_f = mass of fuel in pound mass (lb_m) per injection.

t = length of time which injector is open in milliseconds (ms)

In summary, the air mass flow rate is computed using the piece wise linear relatipnships given in Table 1. The inverse of the speed is computed using equation 3. The mass of air induced per cycle is computed using equation 2. The mass of fuel to be injected per injection is computed by multiplying the mass of air by the specified fuel-air ratio. The length of the injection pulse computed using equation 4. The injections are held open for this prescribed time each cycle.

CHAPTER III

THE SPARK IGNITION CONTROLLER

3-1 Introduction

The microcomputer spark controller, designed for this research was an open loop control system. The microcomputer computes the angle of spark advance and spark duration or "dwell" based on the engine speed, rpm. The system is designed so that ignition timing can easily be advanced or retarded based on a Piecewise linear relation of the engine speed.

3-2 Literature Review

Electronic Ignition control systems, like the electronic Air-Fuel ratio controllers, have been the subject of substantial research efforts by the Automotive Industries. The point in the cycle where the spark occurs must be regulated to ensure maximum performance of the engine at different speeds and loads. Also air pollution control is related to the spark advance control. During the early 1970's in an effort to meet government exhaust emission requirements it has been necessary to retard the spark by as much as 10 degrees at idle and at low speeds (17). The addition of catylic converters to remove pollutants during the mid-seventies has permitted engine manufacturers to again time engines for smooth and economic performance.

Spark timing can also be controlled to reduce fuel octane requirements, particularly at low speeds. For example, the octane requirement can be reduced from 105 to 85, by advancing the spark timing from 16 to 34 degree of crank shaft (18).

The conventional ignition system with mechanical breaker points is inexpensive, simple to maintain, and is generally adequate for low and medium speeds and loads. Its faults become apparent with high-compression engines or with high speeds of operation. The following are some of the disadvantages of conventional ignition system (17):

1. Poor performance at high engine speeds, over 4000 rpm, because of current limitations and inertia (point bounce) caused by the mechanical breaker points.
2. Inability to fire partially-fouled spark plugs, because of a slow voltage rise-time.
3. Relatively short life of the breaker points because of high current flow at low speeds.
4. Relatively short life of the spark plugs, because of the high-energy discharge at low speeds.
5. Poor starting because of slow-opening of breaker points at cranking speeds.
6. Poor reproducibility of secondary voltage rise and maximum value.

The ability of a transistor to interrupt a circuit carrying a relatively high current makes it an ideal replacement for the breaker points and condensor. Electronic ignition systems have been used as standard equipment on some of the 1975 or later model cars. This system turns on and off a transistor cuircuit by a set of trigger light and light chopper which are mounted on the distributor plate. By using this system contact points and condensor are eliminated. The trigger light consists of an infra-red light-emitting diode and a photo transistor receiver (19). This system also included a central box which is a solid state electronic switching device. The light chopper rotates with the distributor shaft and its blades pass between the infra-red sending unit and the phototransistor-receiver. As each opening between the chopper blades pass the sending unit, a signal is sent to the power-switching transistor in the solid state control box. The length of time for spark firing or the "dwell" is built into the light chopper. Electronic ignition systems are also available to retrofit older model cars which have conventional ignition systems. These systems whether installed as original equipment or retrofit to older models utilize the conventional mechanical vacuum and speed spark advance systems.

The use of microcomputers for ignition control, is being explored by several research institutions. An electronic ignition control system has been designed by D. Bert and Van De Casteele at the University of Ghent, Belgium (20). This system was a simply programmable electronic ignition control system that could be applied to the study of engine behaviour. This apparatus permitted an easy change of the advance or retard characteristics as a function of rpm or vacuum. This system is built out of a disc with 20 cm diameter and 180 holes which was fixed on the engine crank-shaft. The detector system was built up with a set of four phototransistors illuminated by four lights through the holes of the disc. The electronic circuitry consists of a set of TTL integrated circuit including a schmitt trigger, several monostable multivibrators a comparator, several binary counters and a digital to analog convertor. An optical transducer generates impulses at 80° before TDC. A second optical transducer generates impulses every 0.5°. The synchronizing first impulses (80°btdc) enable an electronic counter to count down the second impulses (0.5°). The counter output feeds a digital to analog converter (DAC) and in this way a voltage (or current) linearly decreasing with number of

.5° impulses is obtained. The first impulses (80°btDc) also feed a speed to voltage converter (SVC) that gives an output voltage or current linearly increasing with the speed or rpm. In order to take account for the spark advance control curve, a function generator (FG) processes the speed to voltage output voltage. In general a piecewise linear function suffices for the simulation of the advance characteristic of the engine. The output of the DAC and FG are connected to both inputs of a comparator (COMP). The output of COMP changes its state whenever its input voltages become equal and this gives pulse that actuates the electronic ignition system and presents the counter at 111 111 11 or 2 ex 8 or 256. If a vacuum transucer is used it is possible to extend the system with a second function generator adapted for generating an out output that is function of the vacuum. The sum of the outputs of both function generators can then be compared with the DAC output. The resolution for this system was 0.5 degree. This system was tested on an Opel 1900 engine and the system seemed to be very flexible.

3-3 Control Concept and Description of Physical System

The microcomputer spark ignition control developed in this research was an open loop system. The Block diagram of this system is shown in Figure 12.

The speed sensor used in the ignition control system was the same as was used for Air-Fuel Ratio control system. New values of engine speed are read and stored in certain memory locations every cycle of engine. These values were used to determine proper spark advance. The microcomputer was programmed

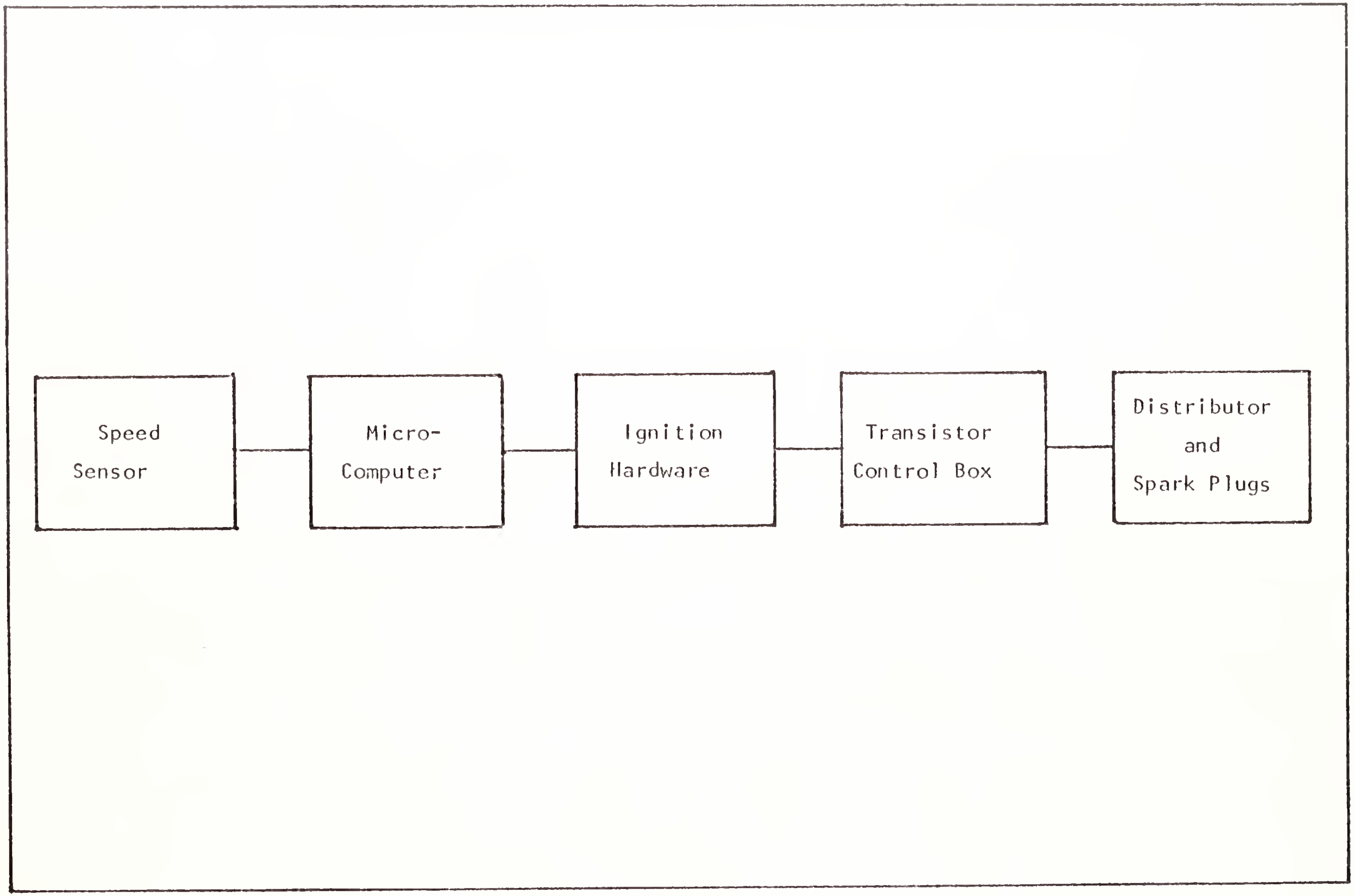


Figure 12. Block Diagram of Microcomputer Ignition Control System

to compute the spark advance based on the rpm of the engine. A plot of the spark advance us. speed for the conventional vacuum and apark advance system which was used by the VW engine used for this research is shown in Figure 13. This relationship was obtained by adding the vacuum and contrifugal advance values given in the 1968 VW manual for distributor type 311905205 (15). The proceedure for implementing this function in the microcomputer will be presented in section 3-4.

The hardware interface between the microcomputer and the ignition system is shown in figure G2 of appendix G . The complete specification of the ignition signal requires the generation and proper phasing of three time interval values, each a function of engine speed. The first, called the ignition phasing time, is defined as the time from the negative going edge of the distributor pulse to the leading edge of the next ignition pulse and is equal to the time for 180 degrees rotation of the crankshaft minus the spark advance in angle of crankshaft rotation minus the phase shift of the distributor signal with respect to the crankshaft in degrees of crankshaft rotation. The second time value is the ignition period which is defined as the time from the leading edge of one ignition pulse to the leading edge of the next ignition pulse. The ignition period is the time required for 180 degrees of crankshaft rotation. The third time value is the dwell time which is defined as the time from the leading edge to the trailing edge of the ignition pulse. It is the time for the dwell angle in degrees of crankshaft rotation. The relationships between these time interval values are shown in Figure 14.

The timing of these three time intervals is accomplished on two twelve bit binary counters (3-74193's). Each counter has a corresponding twelve

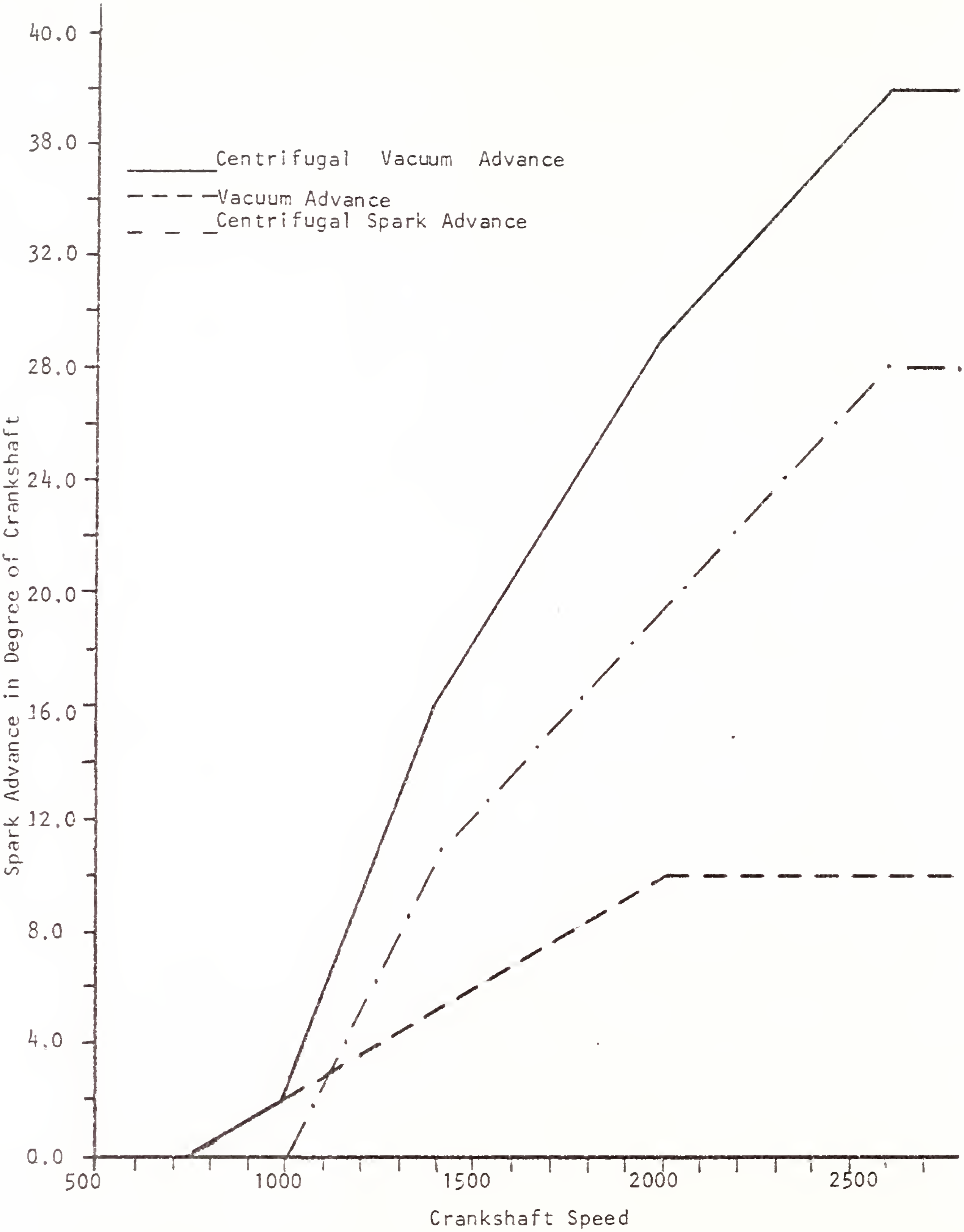


Figure 13. Spark Advance Control Curve

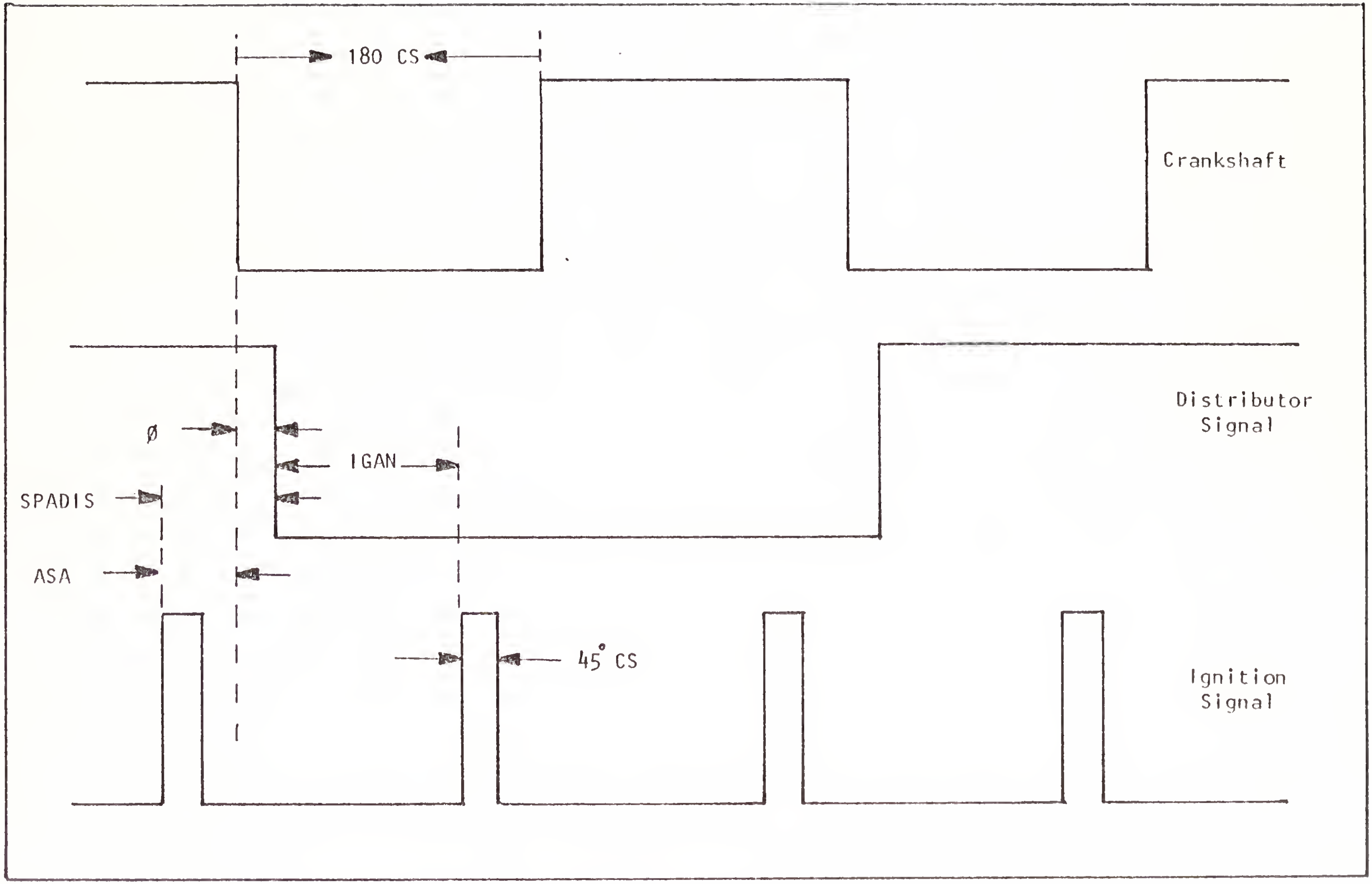


Figure 14. Phase Relationship Between Crankshaft, Distributor, and Ignition Signal

bit latch (3-7475's) which serves as a buffer for the time interval to be parallel loaded into the timer. The clock signal for both of these counters is a 62.5 khz signal obtained by dividing the microcomputer clock (1 mhz) by 16. Note that this clock signal is at exactly twice the frequency of the clock used in the speed sensor. One of the counters is used to time the ignition phasing interval and the ignition period while the other counter is used to time the dwell interval.

The description of the operation of the phasing and period counter follows. Each time this counter reaches a count of zero an ignition pulse is initiated and the counter is parallel loaded with the contents of the latch buffer. As long as the latch buffer holds the ignition period value the counter simply initiates new ignition pulses at regular intervals. Since the engine speed is subject to change the ignition period value must be updated regularly. This is accomplished by transferring the value of the speed sensor counter to the latch during each engine cycle at the same time it is read into the microcomputer. This counter value is equal to the number of cycles of the 31.25 Khz clock during one half cycle of the cam shaft (one revolution of the crankshaft). Since the ignition counter clock signal is twice the frequency of the speed sensor clock the ignition counter will count out the ignition period in exactly one half rotation of the crankshaft (assuming no change in engine speed). Since the latch buffer is refreshed each cycle of the engine no appreciable error occurs due to speed change. The ignition period timing system just described provides a sequence of ignition iniation signals at the correct frequency without intervention of the microcomputer.

In order to obtain an acceptable ignition signal it is necessary to provide correct phasing of the ignition signal with the cycle of the engine. This phase relationship is maintained by the ignition phasing time interval. During each cycle of the engine the ignition phasing time is computed by the microcomputer. At the falling edge of the distributor pulse the ignition phasing time is parallel loading by the microcomputer into the ignition phasing and period counter. Since the parallel load over writes the existing count the ignition phasing time corrects the ignition phase to account for changes in speed, changes in spark advance, and any errors introduced by the sequencing of the signals.

The final timing interval required to define the ignition signal is the dwell time. The dwell time interval is counted out on another counter. Any dwell angle (in degrees of crankshaft rotation) can be obtained by multiplying the speed sensor count by the appropriate fraction and loading the dwell counter latch buffer regularly from the microcomputer. Certain dwell angles can be obtained without the intervention of the microcomputer. The system used for this study obtains a 45 degree of crankshaft dwell without use of the microcomputer. This is accomplished by shifting the speed sensor count right two bits and loading it into the dwell interval buffer. Each bit the count is shifted is equivalent to dividing the value by two. The difference in the clock frequencies accomplishes an additional division by two. The combined effect is to divide the crankshaft rotation by eight yielding a 45 degree dwell. The dwell interval buffer is refreshed each cycle of the engine to provide correction for changes in engine speed. Loading of the dwell interval into the counter is accomplished by the signal which initiates the ignition pulse.

The ignition signal is produced by a J-K Flip Flop (7476). The borrow outputs of the dwell counter and the period and phase control are connected espectively to the J and K inputs to the Flip-Flop. The borrow outputs of the counters go low on the clock pulse when the count reaches zero. The transition of the borrow output of the period and phase counter initiates the ignition pulse by driving the output of the Flip-Flop high. It also initiates the transfer of the dwell time into the dwell counter and loads the period into the phase and period counter. The subsequent transition of the borrow output of the dwell counter terminates the ignition pulse by driving the output of the Flip-Flop low. The output of the Flip-Flop drives the input to the Electronic Ignition counter box which controls the ignition discharge.

3-4 Mathematical Description

In order for the microcomputer to compute the exact angle of spark advance, a set of piecewise linear equations of spark advance vs. speed of the engine was obtained from the graph given in Figure 13. These equations are listed in Table 2.

ASA = 0	$0 \leq N \leq 750$
ASA = 0.008 N-6	$750 \leq N \leq 1000$
ASA = 0.035 N-33	$1000 \leq N \leq 1400$
ASA = 0.021667 N-14.33	$1400 \leq N \leq 2000$
ASA = 0.015 N-1	$2000 \leq N \leq 2600$
ASA = 38.0	$2600 \leq N$

where

N : engine speed (rpm)

ASA: angle of spark advance (degrees of crankshaft rotation)

Table 2: Piecewise Linear Model of Angle of Spark Advance vs. Engine Speed

Ignition Phasing Angle which is defined as IGAN, and is shown in Figure 14 is computed by Equation (1)

$$IGAN = 180 - ASA - \phi \qquad (1)$$

where ϕ is the phase shift between distributor and crank shaft cycle. This phase shift was measured to be 14.0 degrees of crankshaft rotation. The value of IGAN which is computed by equation 1 is in unit of degrees of crankshaft rotation. It is necessary to convert to the unit of time in order to be used by the ignition timing counters. The mathematical relationship given in equation 2 provides the ignition phasing time in microseconds.

$$IGTI = (166.0 - ASA)\left(\frac{10^6}{6N}\right) - DT \qquad (2)$$

where

IGTI : Ignition phasing time (μs)

N : Speed of the engine (rpm)

ASA : Angle of spark advance (degree of crankshaft rotation)

DT : Delay time from negative going edge of distributor signal to the loading of the ignition phasing counter (μS).

New values of ASA and IGTI were computed for every cycle of engine as new speed values were read by the microcomputer.

As the result of using twelve bit counters and a (2.5 Khz clock in the ignition timing circuit IGTI has a range of from 16 to 65,536 μs. The resolution for IGTI is 16 μs which corresponds to a maximum crankshaft angle of 0.044 degrees at the minimum speed of 460 rpm. The resolution at 4000 rpm is 0.384 degrees.

CHAPTER IV

THE SOFTWARE

4-1 Introduction

The software developed for this research was one of the major tasks. The programming of the microcomputer was all done in hexadecimal machine code. A floating point binary representation with a 16-bit mantissa and an 8-bit exponent was used for all numerical values. This provided a resolution of 1 part in 65,000 and a range of I1.70 x 10^{38}. By using this type of representation the accuracy of computation was maintained.

The programming of the microcomputer was accomplished with the hexidecimal keyboard and display mounted on the KIM-1 microcomputer board. This device proved to be very helpful for loading the programs and for operating the computer. A Teletype Model 33 teletypewriter was also used for printed and punched paper tape copy. The paper tape reader and the teletype were used to reload programs into computer memory when they were lost due to loss of microcomputer power.

The software may be divided into four classifications: the initialization routine, the background routines, and real time (interrupt driven) routines, and the service routines. The details of these routines and the interaction among them is explained in the rest of this chapter.

4-2 Initialization Routines:

The Initialization sequence was necessary to define certain quantities everytime the microcomputer was reset. By the end of this routine all values used during the computation were given initial values. The flowchart of this program is shows in Figure 15.

The first step in this routine is to initialize the stack, so that the microprocessor may properly process an interrupt. The stack pointer is initialized to location OIFF hexadecimal machine address (21). The next operation sets the interrupt disable bit in the status register. This step is to keep interrupt request signals from effecting the microprocessor until execution of the initialization program was completed.

The next step of this program initializes the status of the input-output registers. There are 15 I/O lines available in the KIM-1 microcomputer. They are divided into ports A and B. Each of the I/O lines may be defined as an input or an output by defining the status of the corresponding bit in the data direction register. The next operation sets the binary mode bit. This step causes the microprocessor to do arithmatic operations in binary.

The next step defines the vector for the non-maskable interrupt. When an interrupt signal is received the microprocessor branches to an interrupt routine. The starting address of this routine is called the interrupt vector. The next three operations of the initialization program establish Air Fuel ratio values and assign initialize values for speed and air flow. The microprocessor uses these initial values at the beginning of execution, before the first true values of speed and air flow are read from the sensors.

The last operation of this program clears the interrupt disable bit which was set before. Finally, the initialization routine stores all constants values required for software programs into appropriate memory locations. A list of these constants is given in Appendix F . The initialization routine is executed once at the beginning of each experiment.

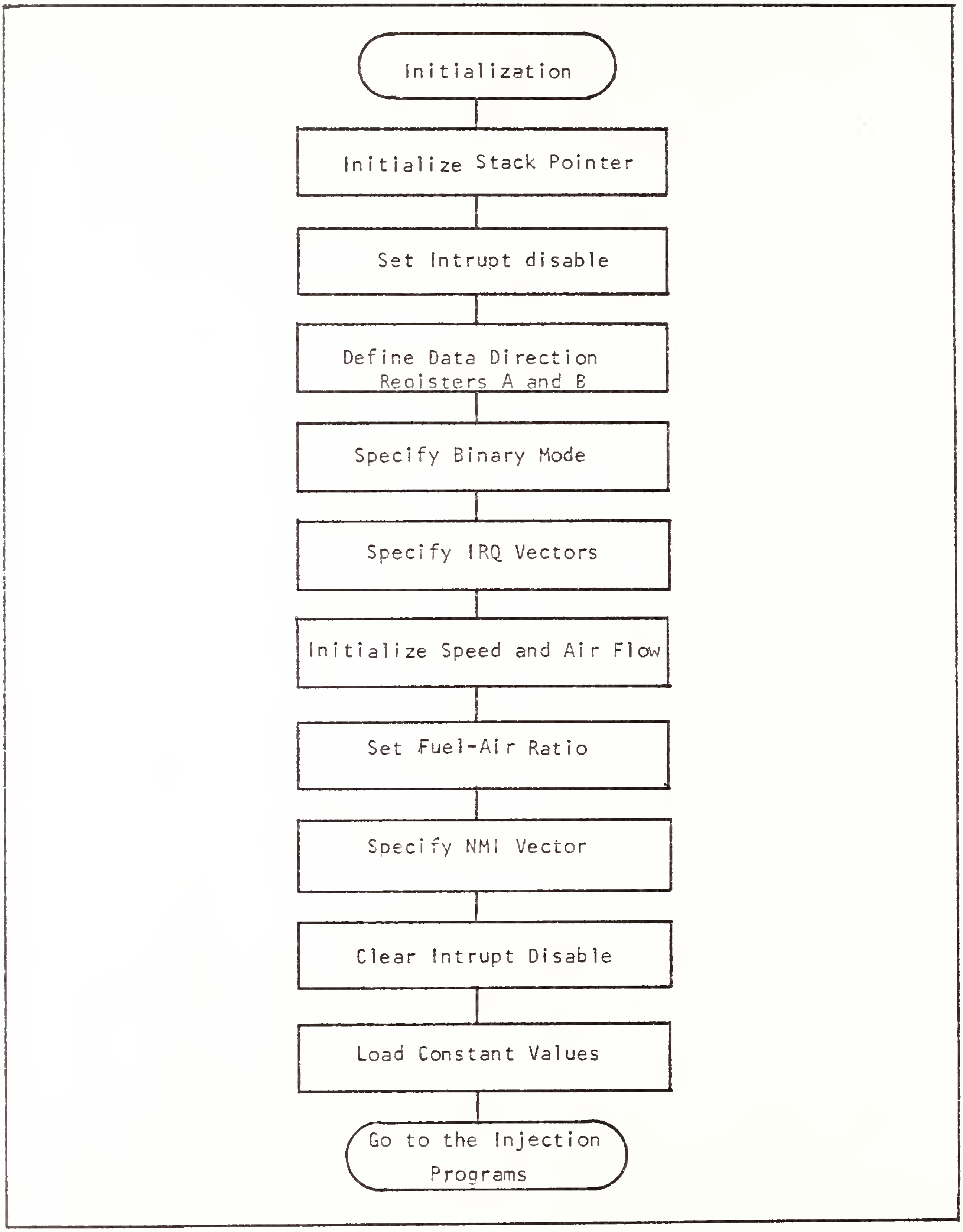


Figure 15. Initialization Program

4-3 The Background Routines

The background routines perform the function of continually updating the control variables; the injection value opening time and the ignition phase time. This is essentially the main program. The program is a large loop which is executed repetitively. The microcomputer executes in the background routines whenever it is not called into the real time routines by an interrupt. The frequency of cycling the background routines is not critical, so long as the control variables are updated often enough to keep up with the changes in speed and load. The operation of the background routines will be described in two parts; the computation of the fuel injection value opening time and the computation of the ignition phase time.

The duration of the fuel injection valves opening is based on the mathematical model which was introduced in section 2-4. Two subprograms are required to complete the computation of injection time.

The first subprogram converts the voltage of air flow sensor to value of air flow rate. Figure 16 shows the flow chart of this subprogram. This program scales air flow rate based on the relationship of the graph in Figure 10 and the piecewise linear equations given in Table 1. The air flow sensor voltage is compared to the ranges corresponding to the different piecewise linear equations. When the correct range is found the corresponding equation is used to compute the air flow rate.

The second subprogram converts the mass of fuel per injection to duration of injection time. This subprogram is based on the graph of Figure 11, and the corresponding linear relation. Figure 17 shows the flow chart for injection program.

The first operation of the injection program calls the subprogram to

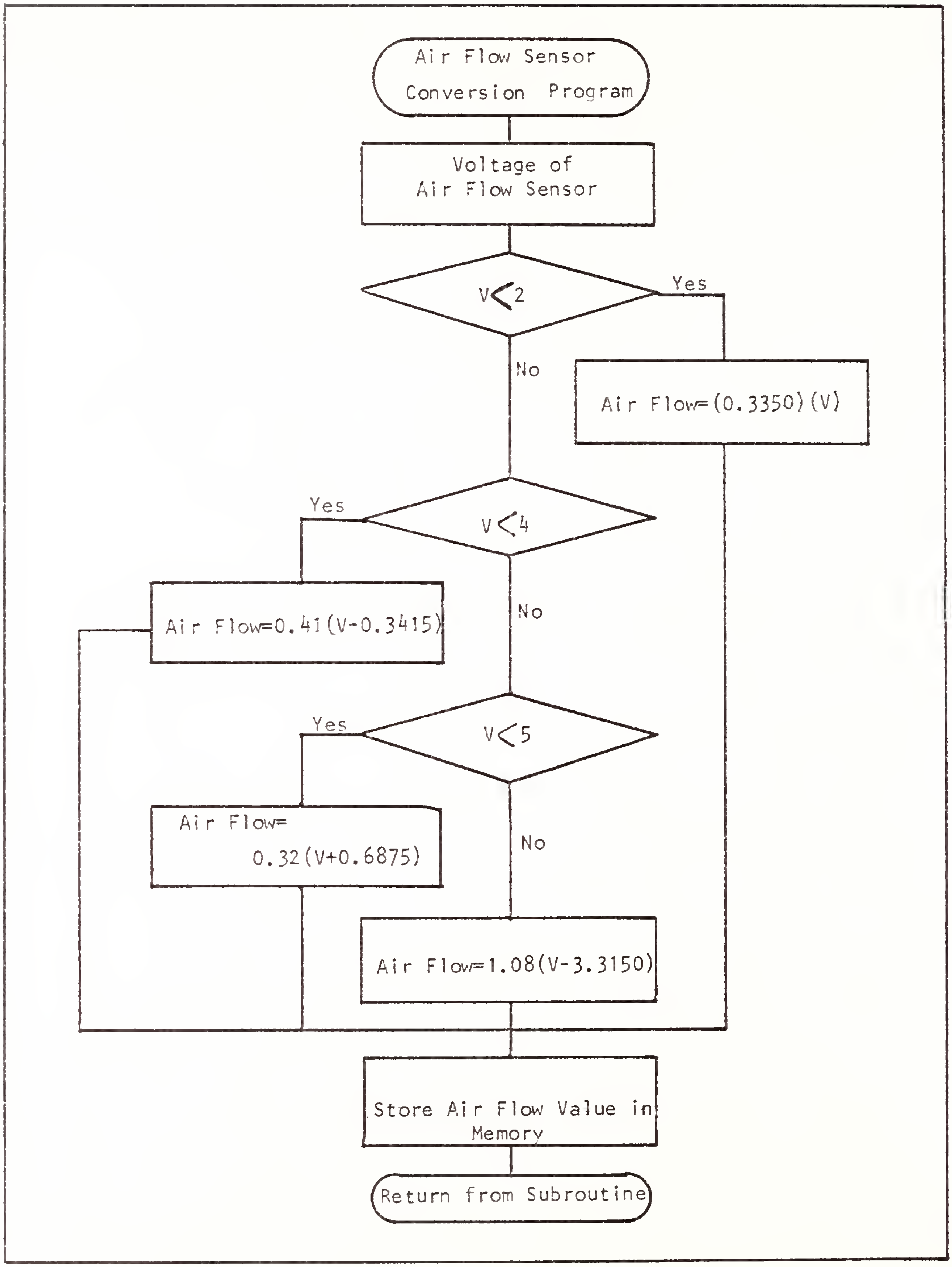


Figure 16. Air Flow Sensor Calibration Subroutine

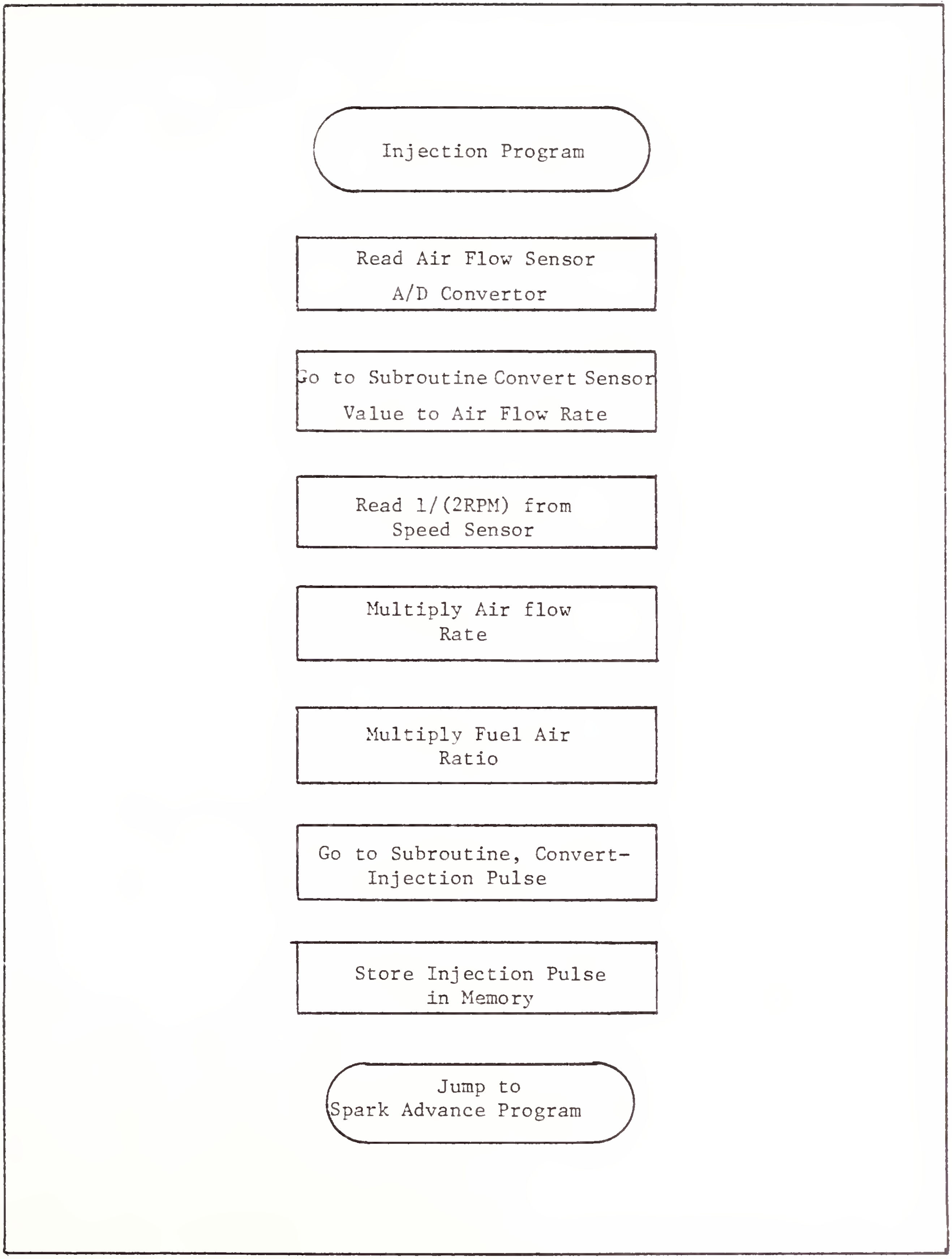


Figure 17. Injection Program

scale the air flow rate. The Air Flow Ratio is multiplied by the specified value of Air-Fuel ratio. This product is multiplied by $1/2N$ which was obtained from the speed sensor. The result is the value of the mass of fuel per injection.

The next operation of this program calls the subroutine to convert the mass of fuel per injection to injection time. The final operation of the injection program is the scaling of the injection time so that it can be used by the interval timer to time out the injection value opening.

Computation of the ignition time control variables was the second objective of the background routine. This portion of the program computes the ignition time IGTI from the relationship given in section 3-4. The ignition time routing also uses two subprograms. The first one computes and scales the speed value while the second subroutine compute the angle of spark advance.

The first subprogram requires a division subroutine to compute the speed value from the value of $1/2N$ which was read from the speed sensor. The value of speed is used to compute the angle of spark advance. The division routine is one or two service routines to be described later.

The second subroutine determines the angle of spark advance, ASA, based on the relations given in Table 2 of section 3-4. The angle of spark advance is a function of speed. The first step of this subprogram tests the speed and determines the range and corresponding equation. The next operation of this program computes the angle of spark advance by the corresponding relation. The flow chart of this subprogram is given in Figure 18.

The final operation of this routine uses the angle of spark advance and speed to find and scale the ignition phase time. The injection time program and the ignition phase programs are listed in Appendix F . Figure 19 shows the flow chart for ignition time program.

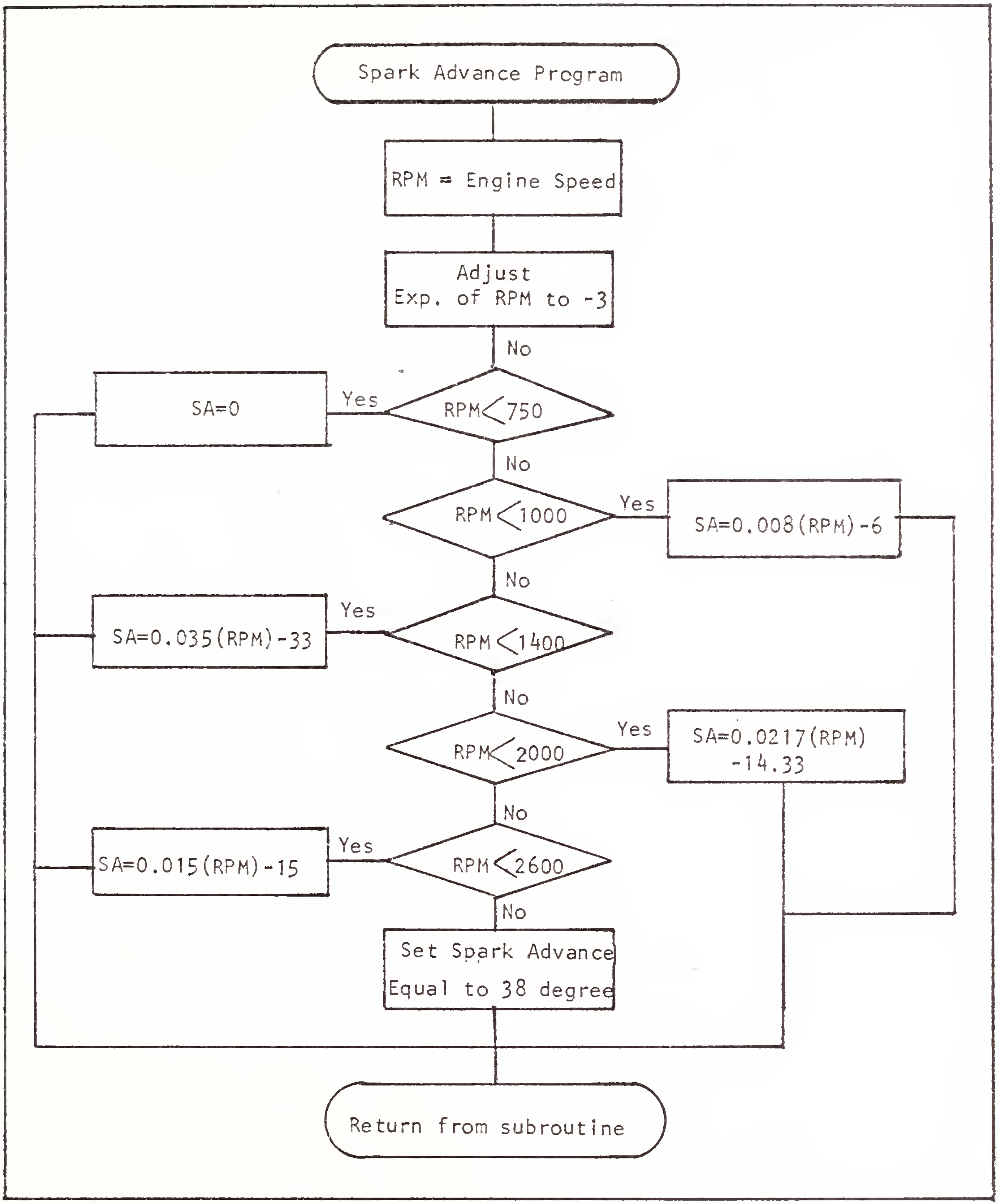


Figure 18. Ignition Spark Advance Program

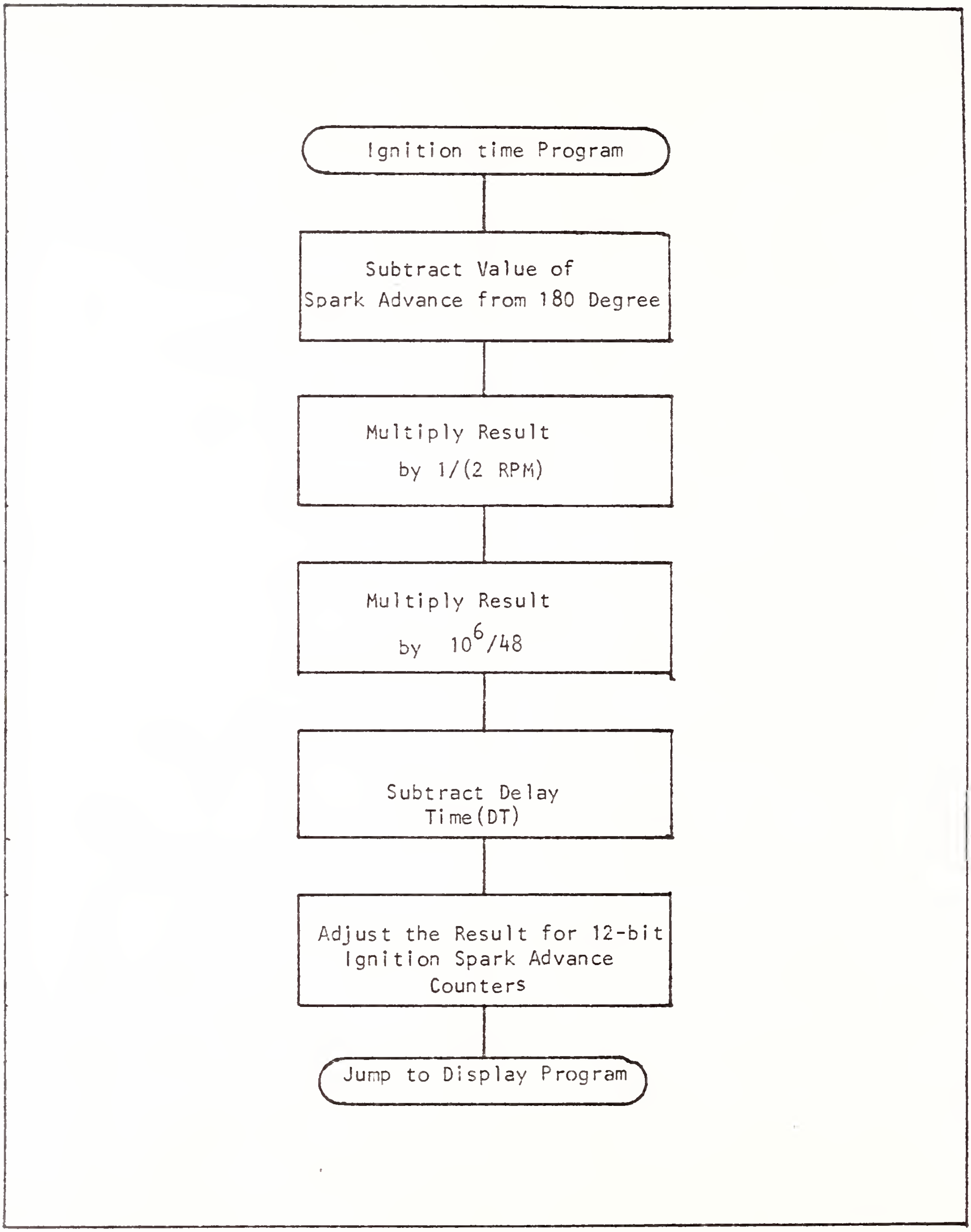


Figure 19. Ignition Time Program

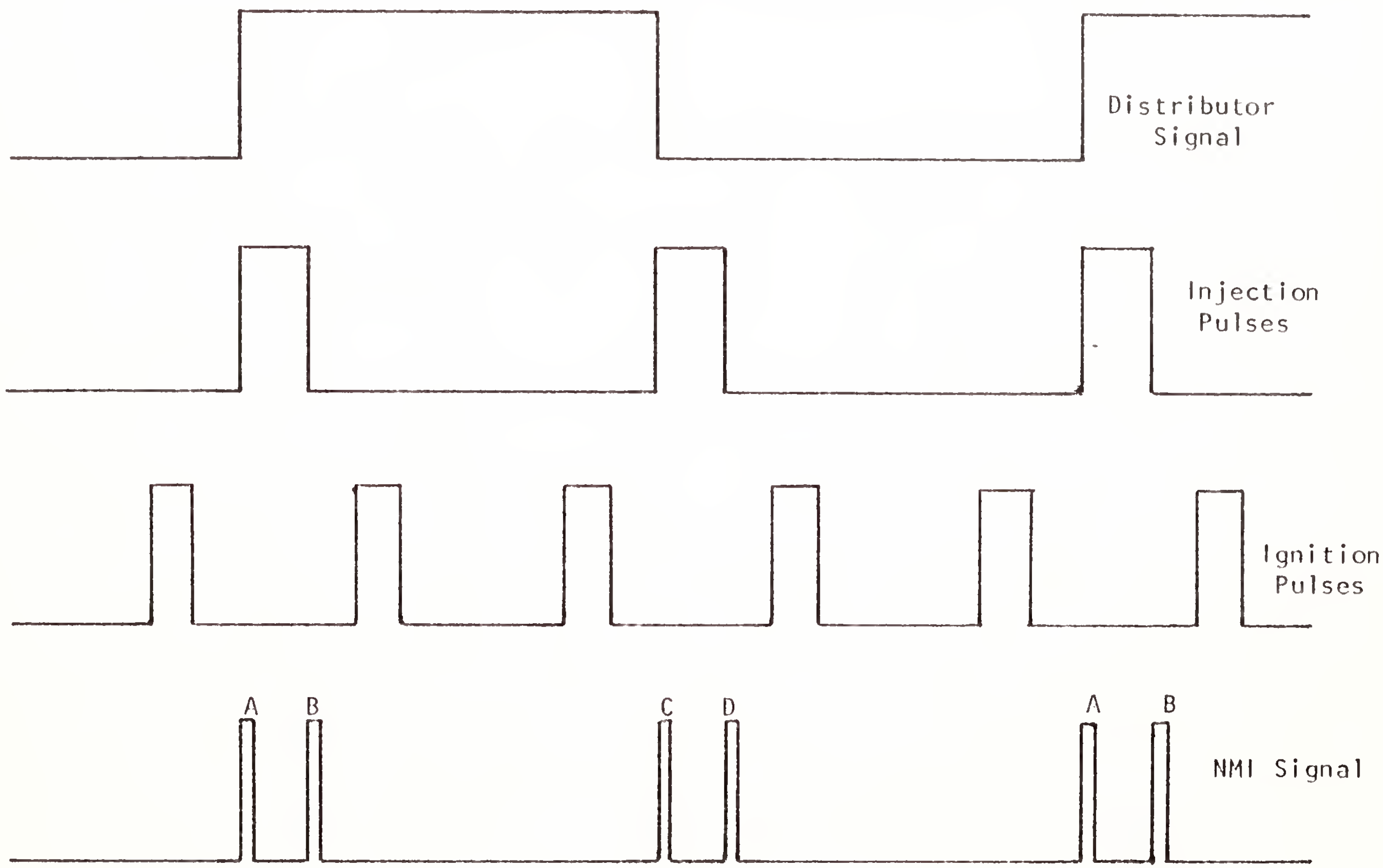
4-4 The Real Time (Interrupt Driven) Routine

The interrupt capability of the microprocessor is used when an external event has occurred and special service or immediate attention of microprocessor is required. When an interrupt occurs, the status register and the program counter are stored on the stack. At the end of the interrupt service the status register and the program counter are restored to the values they had at the time the interrupt was taken. In this way the computation continues at the completion of the interrupt from the same point it left at the beginning of the interrupt.

The KIM-1 microprocessor has two kinds of interrupts: The interrupt request and the non-maskable interrupt. The interrupt request can be disabled under program control and can thus be ignored. The non-maskable interrupt can not be disabled or ignored. As soon as the non-maskable interrupt signal transition occurs the microprocessor sets up the stack and transfers to the interrupt service routine.

For this project only the non-maskable interrupt was used. There were two sources of interrupt signals: the distributor signal and the fuel injector timer. There are four different sets of actions taken depending on the source of the interrupt signal and the polarity of the distributor signal at the interrupt time. The distributor signal is a square wave signal synchronized with the cycle of the engine such that two fuel injectors begin their injection time at the rising edge and two at the falling edge of the square wave. The four sets of action with the corresponding interrupt source and distributor signal polarity are summarized in Figure 20.

The real time program was the most complicated program in this project. The flow chart of this program is shown in Figure 21, and the listing is given



A: Turn Injection on & Set Injection Timer

B: Turn Injection off & Read Air Flow Sensor

C: Turn Injection on , Set Injection Timer , & Set Ignition Phase Timer

D: Turn Injection off & Read Speed Sensor

Figure 20. Phase Relationship Between Distributor, Injection Pulses, Ignition Pulses, and NMI Signal

in Appendix F .

The first operation in this routine was to save the contents of the accumulator by pushing it to the stack. The next operation identifies the source of the interrupt. The injection signal is turned on by the microcomputer every revolution of the engine on both edges of the distributor signal. These pulses are created by setting an out-put bit high. The fuel injection interval timer is started by loading the interval timer register with the computed injection time value. The KIM-1 Interval Timer counts down from the specified value of from 1 to 256 at a clock rate of 1, 8, 64 or 1024 μ sec. per count. The clock rate is determined by the address where the count value is written. The timer can be programmed to generate an interrupt when the counter counts down to zero (22). For the purpose of this work a clock divide rate of 64 microseconds per count with the ability of generating an interrupt was used. When interval timer counts to zero the output bit used to generate the injection pulse is set low.

While the interval timer is counting down the injection time, the computed value of ignition phase time is loaded into the ignition counter every second revolution of the engine. The ignition phase time is loaded into the ignition time during the engine revolution when the distributor signal is low. After completion of injection time the injection timer generates an interrupt. The injection bit is set low (injectors turned off) and then either the air flow sensor or speed sensor is read depending on whether the distributor signal is high or low. The speed sensor value and air-flow sensor value had to be scaled and adjusted to floating point binary number during this program. Following the reading of the speed sensor the value from this sensor is loaded into the ignition counter latch. The final operation of interrupt sequence retrives the content of the accumulator from the stack and returns to the

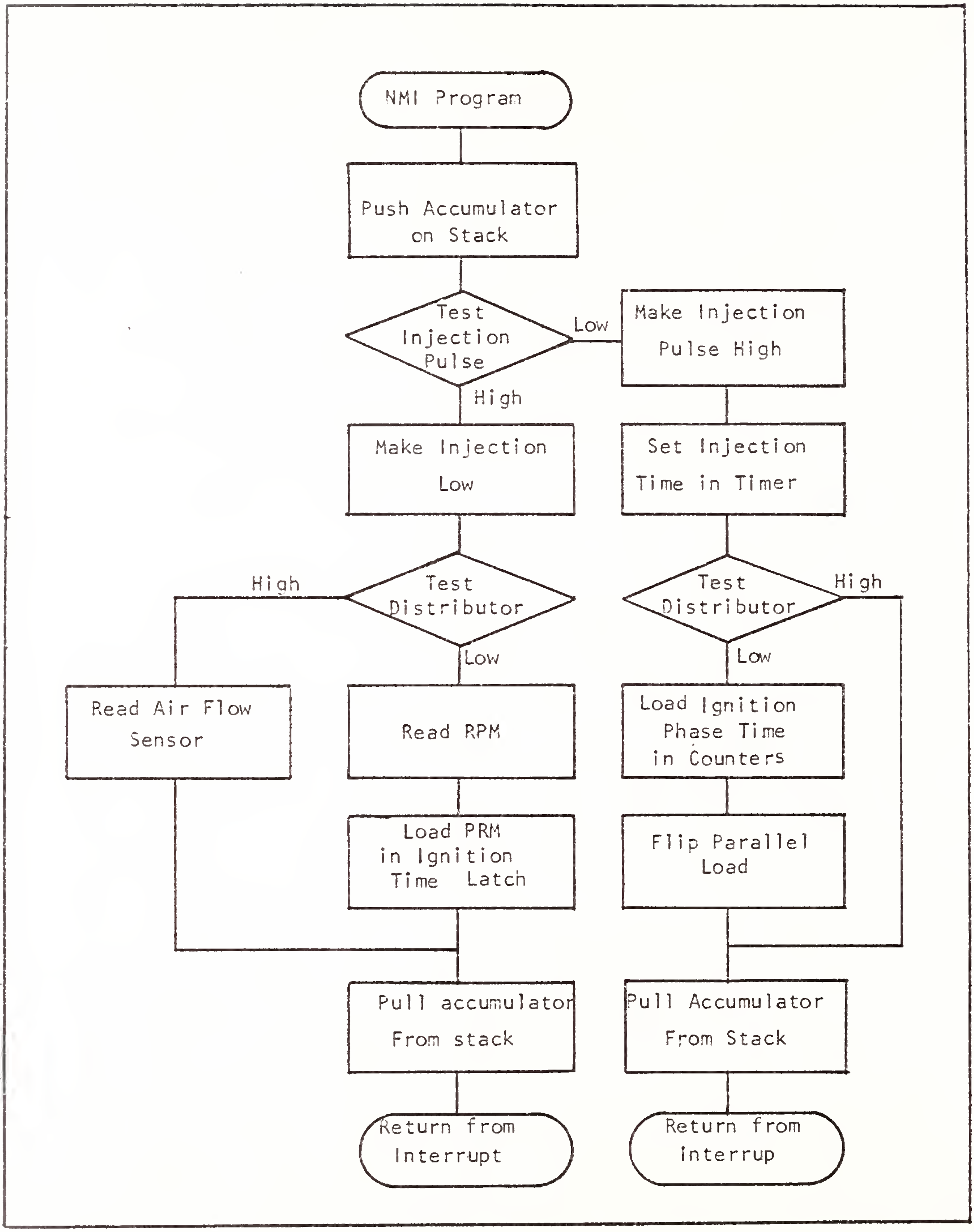


Figure 21. Non-Maskable Interrupt

background routine from the interrupt.

4-5 Service Routines

There are five service routines available to the other programs. They are the floating point arithmatic routines for multiplication, division, and addition and subtraction; a routine for displaying values on the seven segment displays; and a routine for storing and analyzing data.

The KIM-1 microcomputer is able to perform the addition or subtraction of two eight bit values. However, multiplication, division, addition and subtraction of values expressed in the floating point format was needed.

The multiplication subroutine was written to multiply the two sixteen bit signed binary numbers and to add the two eight bit signal exponent. The result of the multiplication was shifted and truncated to the same format as the input. To provide the needed accuracy, the subroutine operations are done in double-precision with the sign bit at bit 16. Basically, the multiply routine is a series of tests and shift of the multiplier and multiplicand. Figure 22 shows the flow chart of this program. For higher degree of accuracy, at the beginning of the program, both the multiplier and the multiplicand are shifted so that their highest bits after the sign bits are "1" for positive numbers and "0" for negative numbers. This operation is done at the beginning of all arithmetic programs. Appendix F gives the listing of the multiplication program.

The division program was also written to perform double-precision signed, floating point division of two sixteen bit numbers. The division routine, as shown in Figure 23, consists of a series of trial divisions, each of which will be made by attempting to subtract the divisor from the dividend (23). If the result is negative, the divisor will not "go"; a 0 is therefore placed

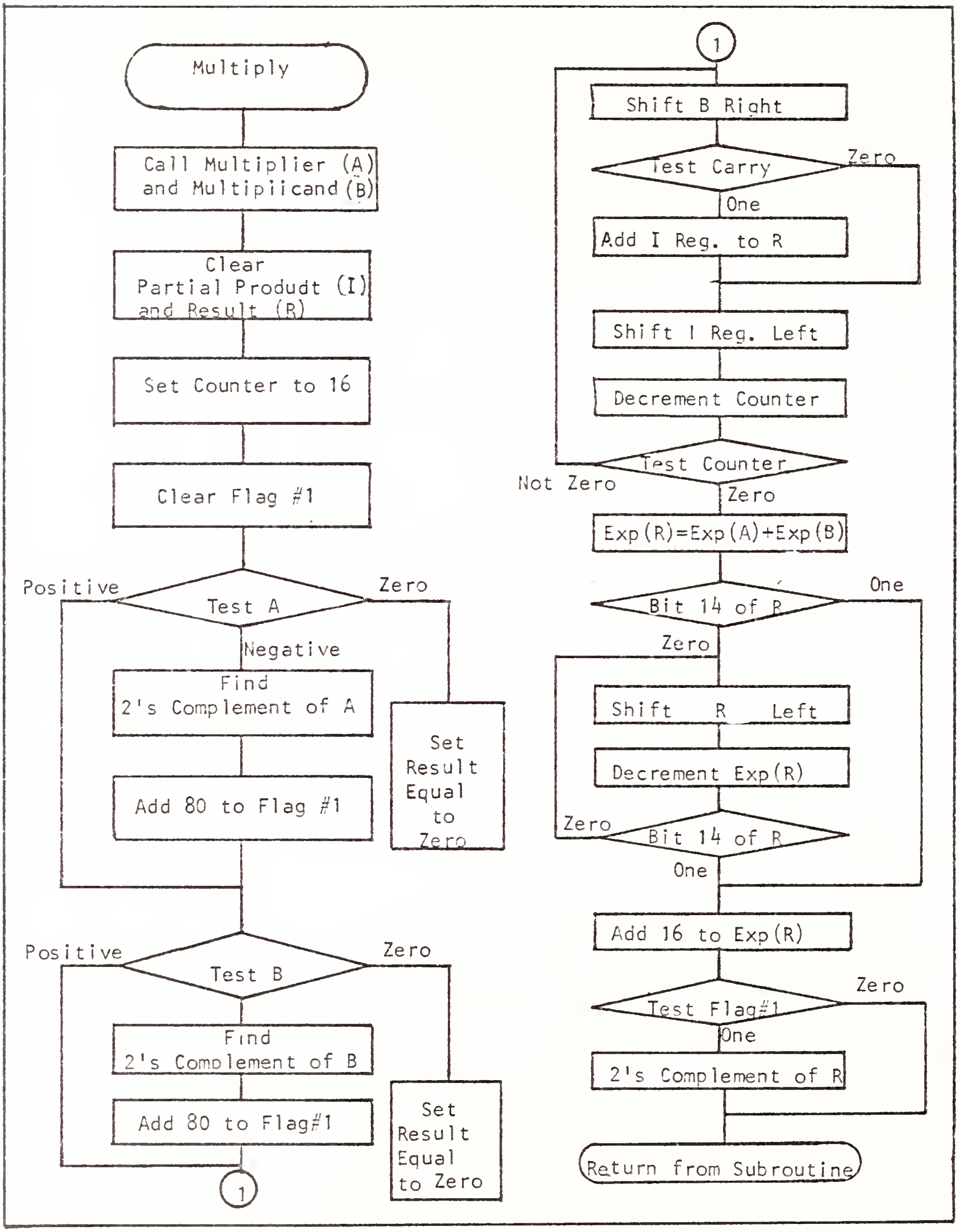


Figure 22. Multiplication Subroutine

in the right most bit of the quotient, and the dividend is restored by adding the divisor to the result of the subtraction. The combined quotient and dividend will then be shifted left.

If the result of a trial division is positive, there is no need to restore the partial dividend in the dividend register. A 1 will be placed in the rightmost bit of the quotient, and the dividend and quotient will both be shifted left. It should be noted that the mantissa of divisor be larger than the mantissa of dividend. If this condition is not satisfied the dividend can be adjusted by shifting its mantissa to the right and incrementing its exponent.

The subtraction or addition operation was repeated 15 times, once for each bit of the number. The last part of program determines the exponential of partial quotient, and adjusts and final result. Provisions were also made to take care of the signs of both the divisor and dividend, and the final partial quotient. The list of actual division subroutine is given in Appendix F .

In order to perform addition and subtraction of sixteen bit floating point numbers it is necessary to equate their exponents. To insure maximum accuracy in the result the numbers are first adjusted so that their highest order bit (next to the sign bit) is significant (1 for positive numbers and 0 for negative numbers). The adjustment is accomplished by shifting the number left and decrementing the exponent until the highest order bit is significiat. The numbers are then adjusted until the exponent of the numbers are equal. This is accomplished by shifting the number with the smallest exponent to the right and incrementing its exponent until the exponents are equal. At this point the two numbers will be added by adding the low bytes of numbers first followed by the high bytes. A flow chart of this subroutine is shown in Figure 24 and a listing is given in Appendix F .

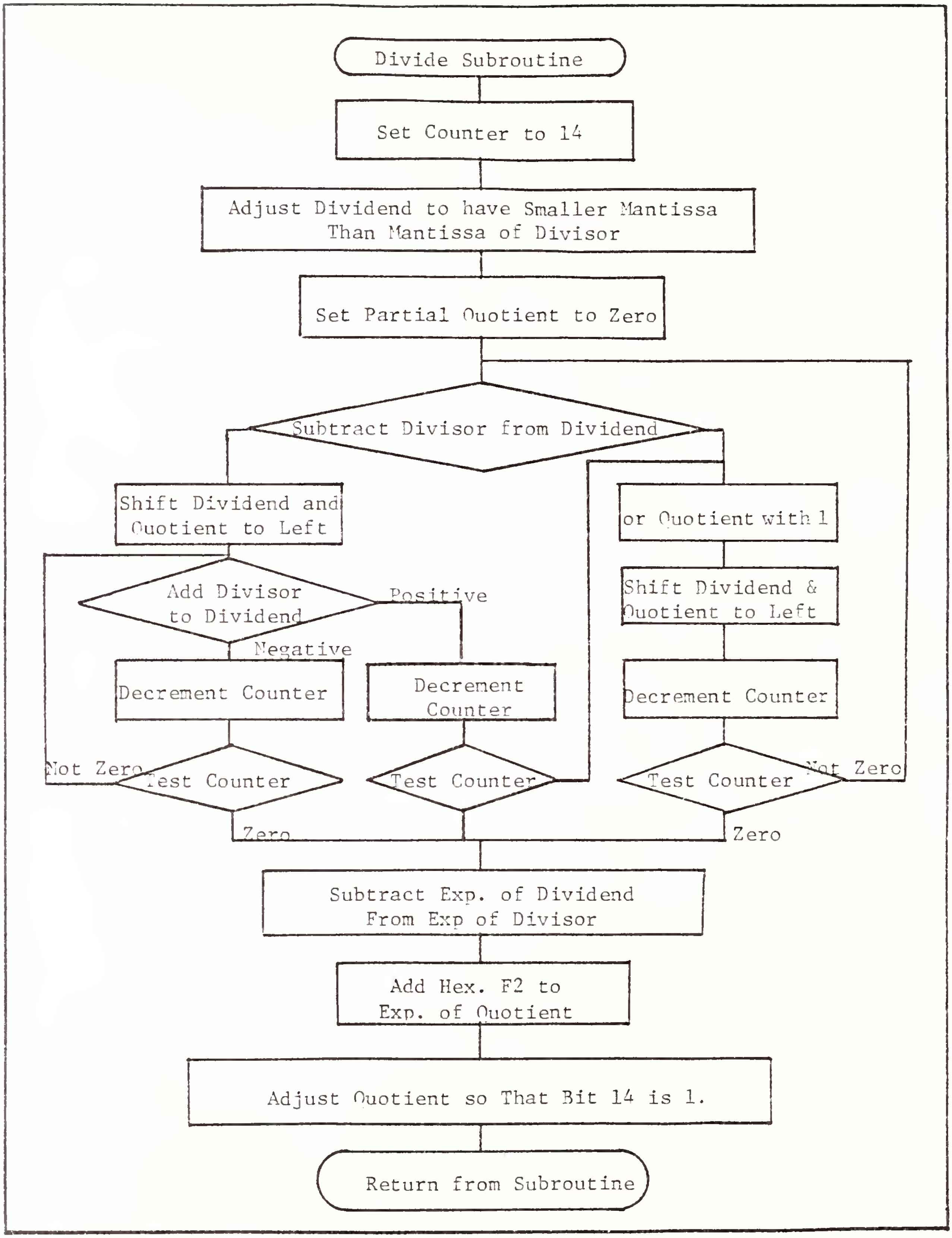


Figure 23. Division Subroutine

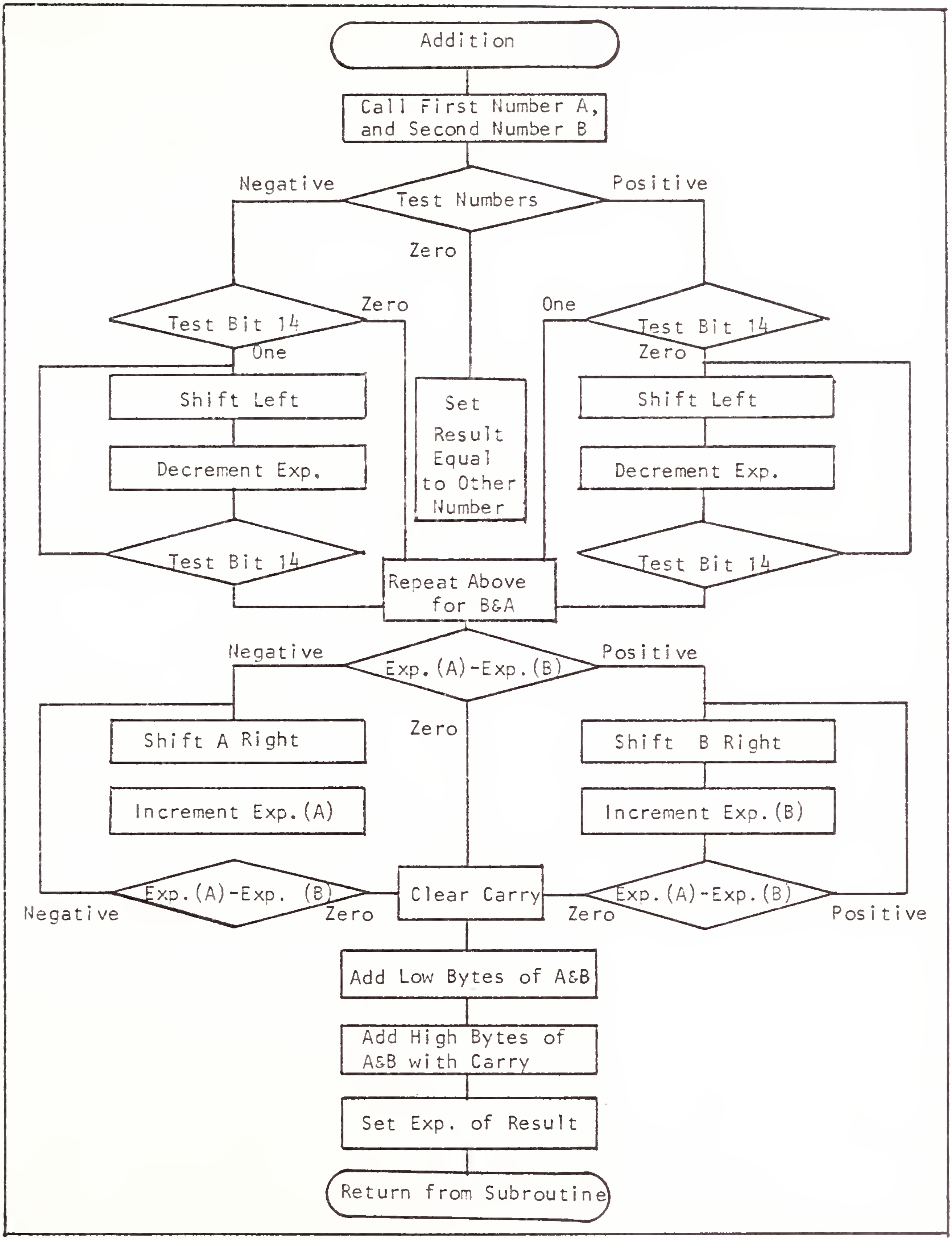


Figure 24. Addition Subroutine

The subtraction subroutine uses the addition program, except at the beginning it changes the sign of the number to be subtracted.

A program that displays a desired number on the microprocessor's seven segment displays was developed to assist with debugging the software and verifying the operation of the hardware. Any value can be set in the display buffer to observe changes in its value as the program proceeds. During operation of the engine, the display program was used to display the engine speed on the first four displays and the injection pulse time adjusted to an 8-bit number is displayed on the last 2 displays. The listing of the display program is given in Appendix F .

A special program was prepared to take several data points and store them at certain memory locations. This program was used for data acquisition and for error diagnostics. The program was executed at the end of the interrupt program and was thereby able to record a data value every two revolutions of engine for up to 100 different readings. This program was not used regularly but it was available to test the software programs or the hardware set up. In order to analyse these data thus collected two other programs were written, one to compute the mean value and other to compute standard deviation of the data. The listing of these programs is given in Appendix F.

CHAPTER V

EXPERIMENTAL AND TESTING PROCEDURE

5-1 Introduction

In this chapter equipment used for experimentation will be explained first. The next section of the chapter will contain a description of testing procedure. Finally, the last section explains the air-fuel ratio and ignition time controller testing.

5-2 Equipment Arrangement

The Volkswagen internal combustion engine and the KIM-1 microprocessor have been described in Chapter 2. Detailed specifications for those are given in Appendices A and B. The engine is loaded with a cradled Hydraulic Pump Dynamometer. A strain gauge load cell on the torque arm of the dynamometer and a magnetic pickup on the drive shaft provide load torque and speed signals. A Daytronic Instrument Module was used to provide digital readouts of load, torque, speed, and power. Two digital counters were used; one for measuring the fuel injection pulse duration, and the other to count the elapsed time for the consumption of a prescribed quantity of fuel during air-fuel ratio tests. A digital multimeter was used to monitor the voltage of the air flow sensor. An oscilloscope was used to observe and measure the various digital signals. A water micro-manometer was used to measure pressure drop across an air flow measuring nozzle. This provided a standard measure of air flow rate. Three power supplies were used to provide dc power for the microprocessor and other equipment. The analog-to-digital convertor and operational amplifiers required ± 15 volts supply, while the microcomputer and TTL circuitry required a + 5 volt power supply. The potentiometer on the air flow sensor used a 10 volt power supply. A sling psychrometer was used to measure the dry-bulb and wet-bulb temperatures of the air. Finally, a mercury barometer was used to measure the atmospheric pressure. Appendix C gives the list of equipment and their specifications. An analysis of the uncertainties associated with the measurements is given in Appendix D.

5-3 Testing Procedures

The software programs for the microcomputer were tested in the laboratory prior to the time the microcomputer was taken to the area in which the engine was located. De-bugging the software programs was the basic part of this test. Arithmetic programs; such as multiplication, division, and addition; were verified separately for the full range of positive and negative numbers. The display program was developed and was of great value in eliminating errors in the software programs.

The interface circuitry was developed and tested in the lab before being applied to the engine. As mentioned before, the distributor signal was not a perfect square wave and the circuitry used to clean this up, as shown in Figure 6, had to be developed and tested on the engine. A substantial effort was required to keep engine noise from causing extraneous signals to be put on some of the lines. To generate NMI pulses on the edges of the distributor signal, a set of monostable multivibrators was used. A great deal of havoc was created when engine noise caused the monostable multivibrators to put out signals when they weren't suppose to. Later, it was decided to generate these pulses using shift registers in conjunction with "NAND" gates. The inverted signal of the distributor was shifted 50 μs to the right and it was passed through a "NAND" gate with the distributor signal. This generated the NMI pulses on the positive going edges of the distributor signal. To generate the pulses on the negative going edges of the distributor signal, the inverted distributor signal and the shifted distributor signal were NANDed together. Figure 24 shows the TTL integrated circuit used to generate NMI pulses. To show how the signals were shifted the phase relation is depicted in Figure 25.

The phase shift between distributor cycle and the crank shaft cycle was needed to compute ignition phase time. This phase shift was measured using one channel of the oscilloscope for the distributor signal and the other for ignition pulses generated by the electronic ignition system. This phase shift was measured with the engine running at 850 rpm and the vacuum advance hose was disconnected. The ignition timing of the VW engine had been set at 0° TDC at 850 rpm with the vacuum hose disconnected (24). The phase difference between the distributor signal and the ignition pulses was equivalent to the phase between the distributor signal the the crankshaft. This phase shift was measured to be 2.745 ms. which is equivalent to 14 deg. of crank shaft.

5-4 Air-Fuel Ratio and Ignition Controller Testing

The first objective of this thesis was to accurately control the air-fuel ratio at any operating condition of the engine. The air-fuel ratio was set at the desired value by the microcomputer's initialization program at the beginning of the engine operation. The air-fuel ratios at which testing was conducted were 14-1, 16-1, and 18-1. While the engine was operating under microprocessor control at the specified air-fuel ration, the operating conditions of the engine were measured experimentally and the actual air-fuel ratio was computed.

To experimentally determine the air-fuel ratio the atmospheric pressure,

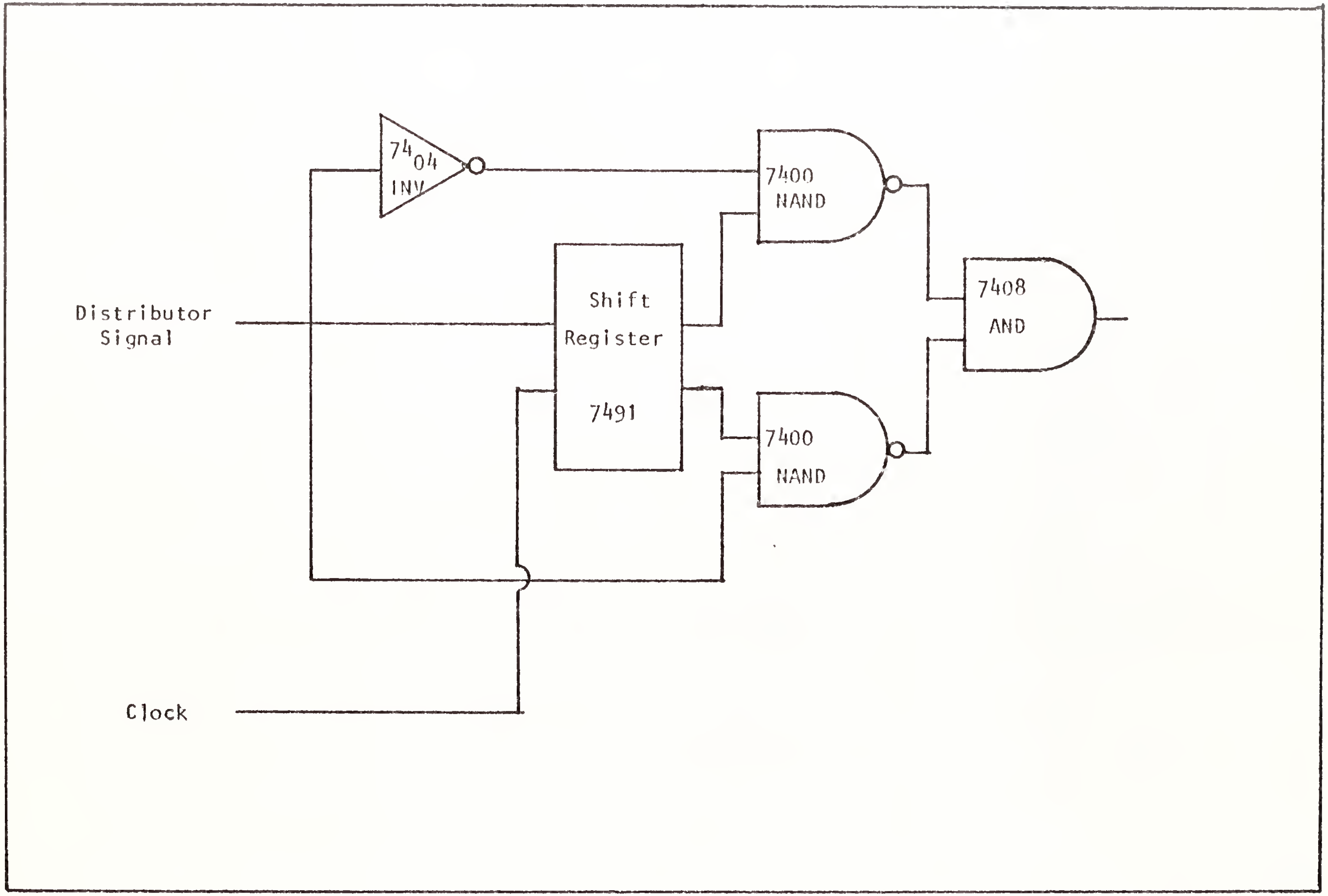


Figure 25. TTL Circuit Diagram for NMI Signal

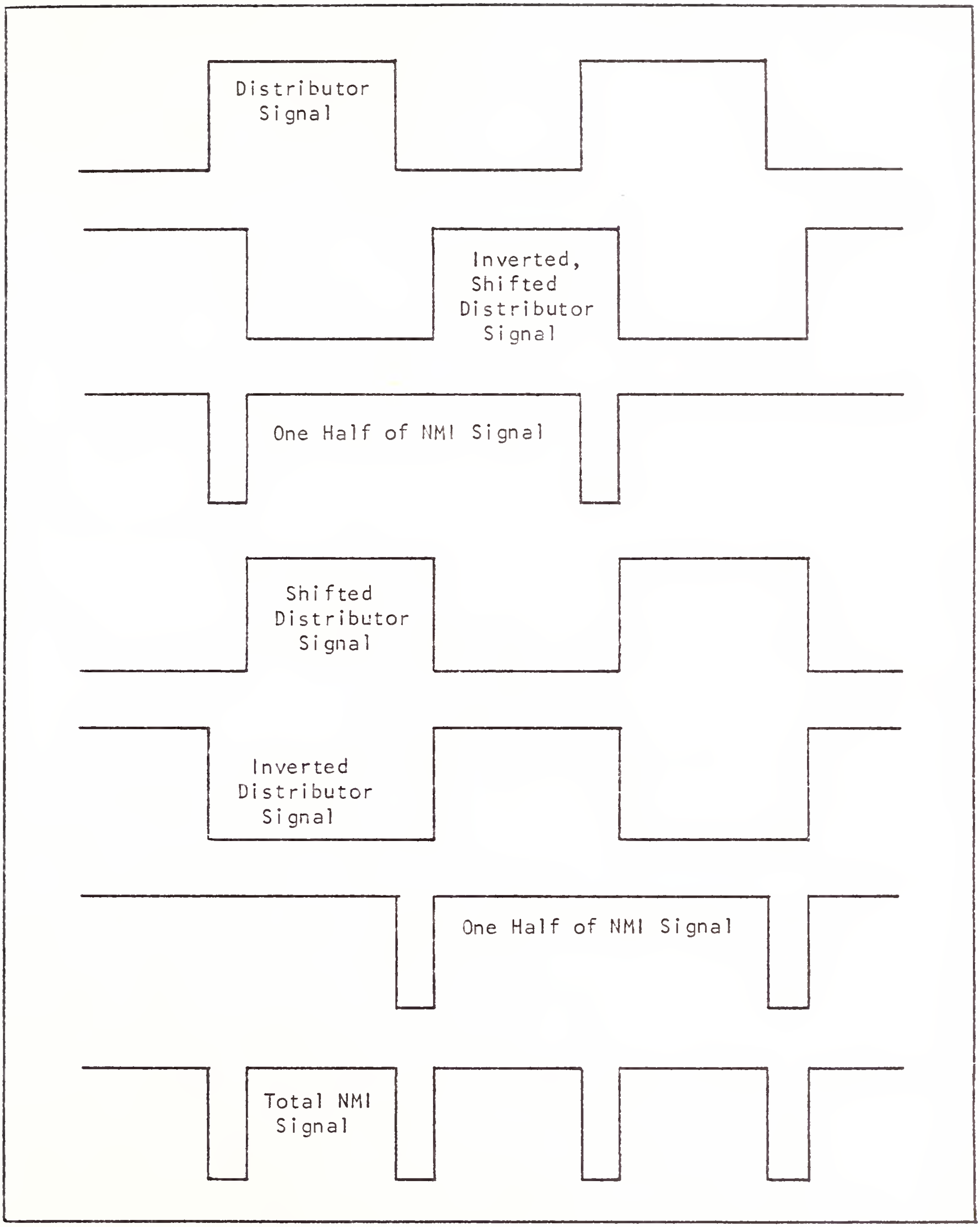


Figure 26. Phase Relation, Generating NMI Signal

room dry and wet bulb temperatures, the quantity of fuel consummed, the time duration of the test, and the pressure drop across the nozzle were measured.

The amount of fuel consumed during each test was specified at a constant 0.40 lb, and the time duration for consuming this amount of fuel was measured using an eletronic counter. A microswitch was used to start and stop the counter as shown in Figure 27. The electronic counter started when the platform of the balance passed through the null position and tripped the microswitch. A 0.40 lb weight was placed on the balance with the full tank. When 0.40 lb of the fuel was comsumed the platform of fuel tank would again pass through null and the micro-switch would stop the electronic counter. The value on the electronic counter was the length of time for the engine to consume the 0.40 lb of fuel.

The air mass flow rate, AMFR was calculated from relations given in reference 25. These relations are as follow:

$$AMFR - (CFM)(DENSA)$$

where DENSA is the density of the air at test condition. This was calculated from:

$$DENSA \quad \frac{(ATMPR)(0.491) - 0.38\left(PW - \frac{(ATMPR)(0.491)(TDB-TWB)}{2700}\right)}{(0.37)(TDB)}$$

in this relation, ATMPR is the atmospheric pressure of the air in inches of Hg which was measured with a mercury barometer located in a nearby room, TDB and TWB are dry-bulb and wet-bulb temperatures respectively in oR, and PW is the vapor pressure of water in the air at the wet-bulb temperature in psia. The value of CFM is calculated from the relation

$$CFM = (62.0524) \quad PMN \left(\frac{0.075}{DENSA} \right)^{0.5014}$$

where PMN is the pressure drop across a 1.59 inch (4.04 cm) ASME long radius flow nozzle. The nozzle, as shown in Figure 28, was placed in one end of a surge tank and from the other end air was drawn by the engine. The pressure drop across the nozzle was measured with a 10 in (25.4cm) water micro-manometer.

The load on the engine was applied by way of an aviation hydraulic pump. Low pressure oil was drawn from a 55 gal (208.2 let) reservoir and pumped back again through a manual pressure control valve and filter. As the pressure against which the pump had to work was increased the torque required of the engine to turn the pump also increased. The pressure control valve provided a mean of increasing the hydraulic pressure. The torque produced by the engine was measured by a strain guage transducer, as shown in Figure 29. The electrical signal from the strain guage transducer was input to the Daytronic Module which provided a digital read out of the load in ft-lb.

The engine speed was obtained by two methods. First, from a fixed magnetic pick-up and a 60 tooth gear mounted on the driveshaft between the clutch and a dynomometer. The pulses from the pick-up transducer were input to the Daytronic Instrument Module which provided a digital read-out of the engine speed. Second, the engine speed measured from the speed sensor and converted by the microcomputer was displayed on the seven segment displays. This value was a hexadecimal number and needed to be converted to a decimal value. It was also possible to measure the engine speed by measuring the distributor signal period using the oscilloscope.

At the beginning of the air-fuel ratio test the engine was allowed to warm up before data was taken. The engine speed and load were set at the desired values. The microcomputer was initialized to control the engine at one of the three specified air-fuel ratio. Data was taken while operating the engine at 3 different speeds and 3 different loads for each value of air-fuel

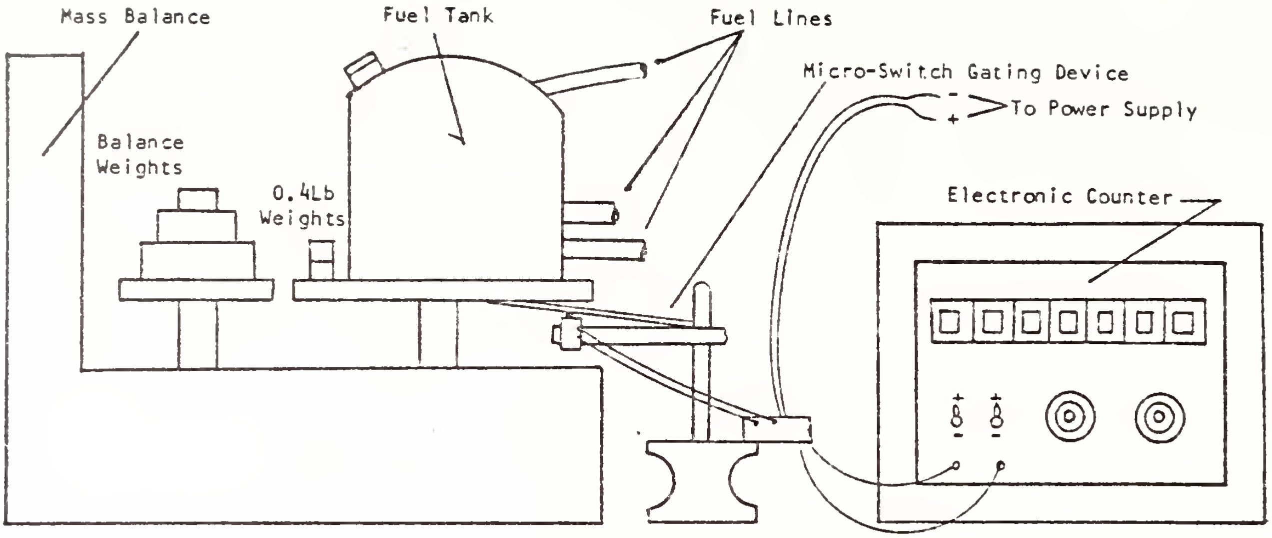


Figure 27. Fuel Consumption Measurment

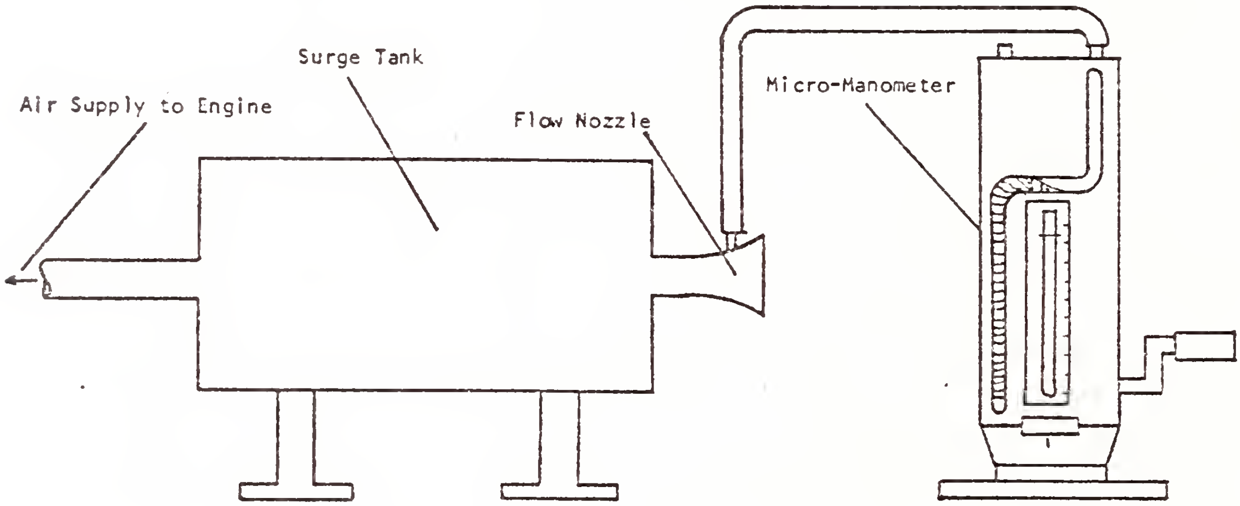


Figure 28. Air Flow Rate Measurment

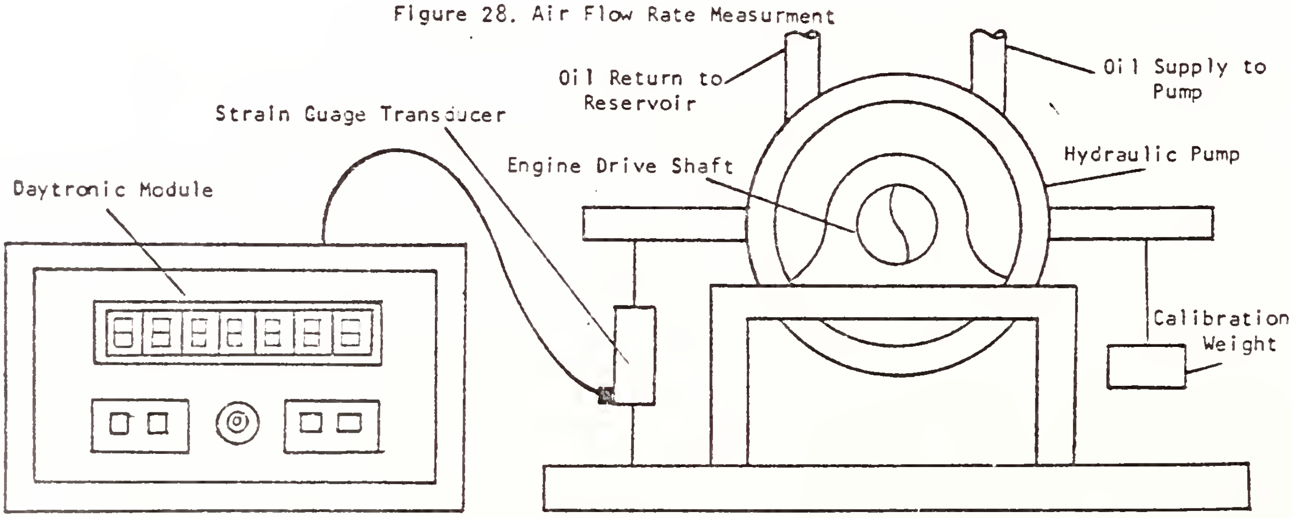


Figure 29. Daytronic,Dynamometer,and Strain Guage Transducer Configuration

ratio. Five tests were made at each set of conditions.

Testing of the air-fuel ratio control was continued until data had been taken at all combinations of speed, load and air-fuel ratio. While data was being taken the fuel injection pulse length was also recorded as measured by the electronic counter and the microcomputer's display. In addition; speed, load, and voltage on the air-flow sensor were measured and recorded.

Microcomputer ignition controller testing was more simple than air-fuel ratio controller testing. The objective of the ignition controller was to accurately control the ignition spark advance and duration of ignition pulse, "dwell". The ignition dwell and spark advance were measured and recorded at the different speed, load, and air-fuel ratio conditions used for fuel injection control testing. A two channel oscilloscope was used to take this data. One channel of oscilloscope was used to display the distributor signal and the other for ignition pulses. The phase difference between starting edge of ignition pulse and the edge of the distributor signal was equivalent to the sum of the spark advance and the phase shift between the distributor and the crank shaft. The dwell was measured from the ignition signal by measuring the duration of the ignition pulses. The values recorded for spark advance and ignition duration were in the units of time, and had to be converted to the units of degrees of crank shaft. This conversion is accomplished by multiplying by engine speed in degrees per unit time.

CHAPTER VI

PRESENTATION OF RESULTS

6-1 Introduction

Data obtained from the testing described in the previous chapter is discussed in this chapter. Section 2 of this chapter describes the results of the air-fuel ratio control tests while the ignation timing control results are discussed in the last section.

6-2 Results of Air-Fuel Ratio Control Tests

The data collected during this research is listed in Appendix H. The results of analysis of the data are shown in the tables and graphs of this chapter. The first set of data was obtained for the two air-fuel ratios of 14-1 and 16-1 over 3 engine speeds from 1200 to 2800 rpm, and for the constant load of 25 lb-ft. The analysis of these results showed a minimum of 9.28% and a maximum of 25% deviation from the expected result. An uncertainly analysis on the air-fuel ratio by Schneck (3) showed only 3.29% for the limit of error, therefore research was continued to find the cause of this deviation. The air flow sensor calibration was checked using its recorded voltage and the calculated air flow from the data. This check did not show anything that would cause this error.

The calibration of the fuel injectors was checked. From the data collected a new calibration of the fuel injectors was obtained. This showed a major difference from the calibration that was obtained from reference 3. The microcomputer was reprogrammed with the new mathematical relations of the fuel injector calibration. A second set of data was obtained at the same conditions of the engine. This gave better results and lower deviations for the air-fuel ratio of 16-1 but not for the air-fuel ratio of 14-1. Analysis of the results showed an error to exist because the points used to calibrate the fuel injectors were too close to each other. The best fit curve through these points gave an inaccurate calibration.

It was decided to recalibrate the fuel injectors with many points widely separated. To obtain this calibration the engine was operated on the Bosch system for several different loads and speeds. The injection pulses were measured on the oscilloscope and data was taken to compute mass of fuel per injection. Figure 11and equation 4 are the results of this calibration. The 3 calibrations described above are compared on Figure 30.

The final data for the air-fuel ratio control was taken based on the last injector calibration for three air-fuel ratios. Figures 31 and 32 compare the air-fuel ratios of 14-1 and 16-1 respectively fro the 3 different fuel injector calibrations. The results of testing for three air-fuel ratios over the engine speeds of 1200 to 2800 are presented in Figures 33 through 35 for load of 10 lb-ft, 25 lb-ft, and 40 lb-ft respectively. Each point on the graphs represents the average of five tests taken at that condition.

After all data was taken, the values of air flow corresponding to the voltages of the air flow sensor were compared to the air flow calculated from the pressure drop across the nozzle. In a few cases there were small differences between these two values. It is believed that the potentiometer on the air flow sensor was not operating properly at all times during the last part of the final tests. In order to best evaluate the performance of the controller in those cases where there was a difference in the value of air flow from the measurements the voltage of air flow sensor was used to compute air

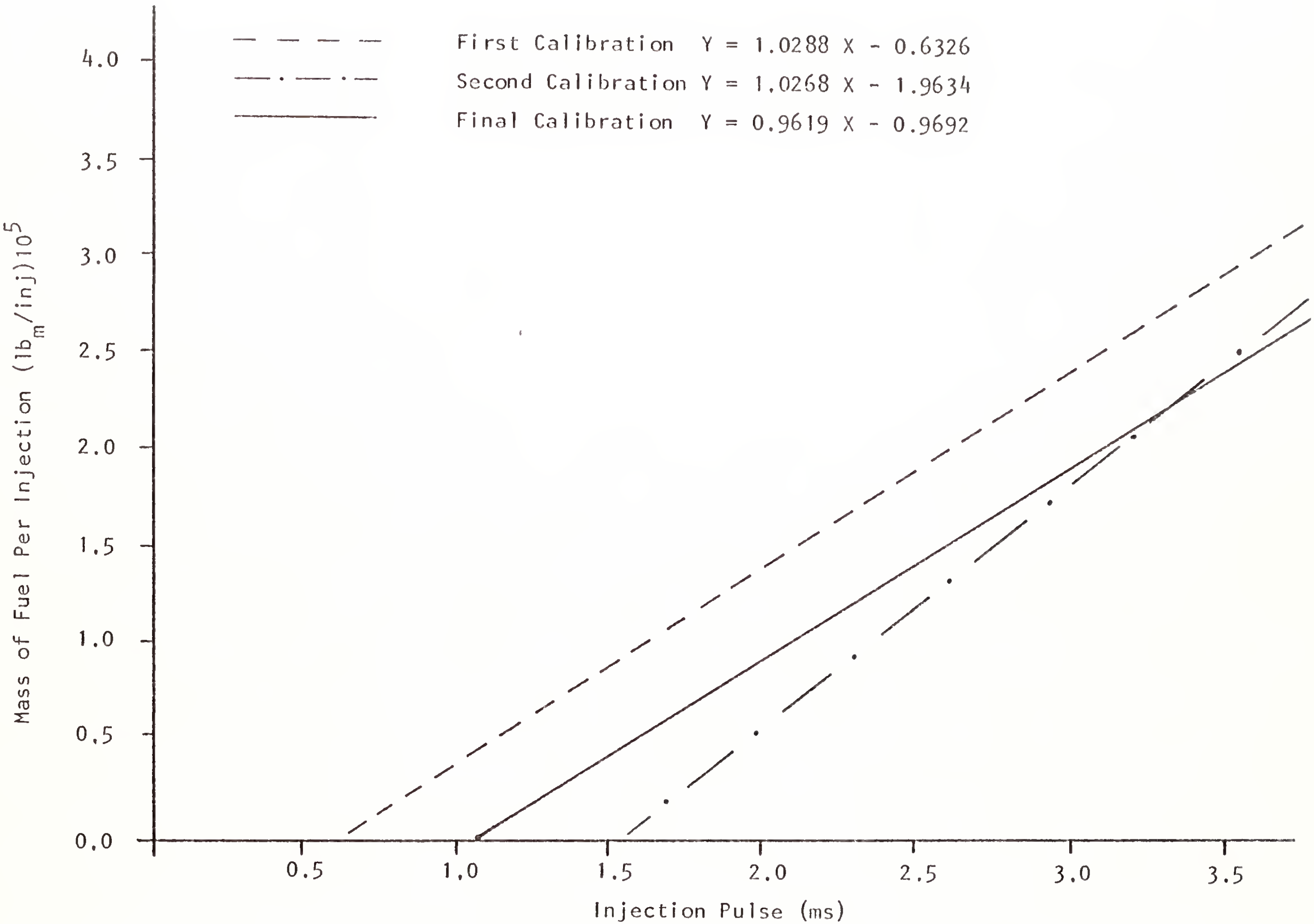


Figure 30. 3 Different Calibrations of the Fuel Injector

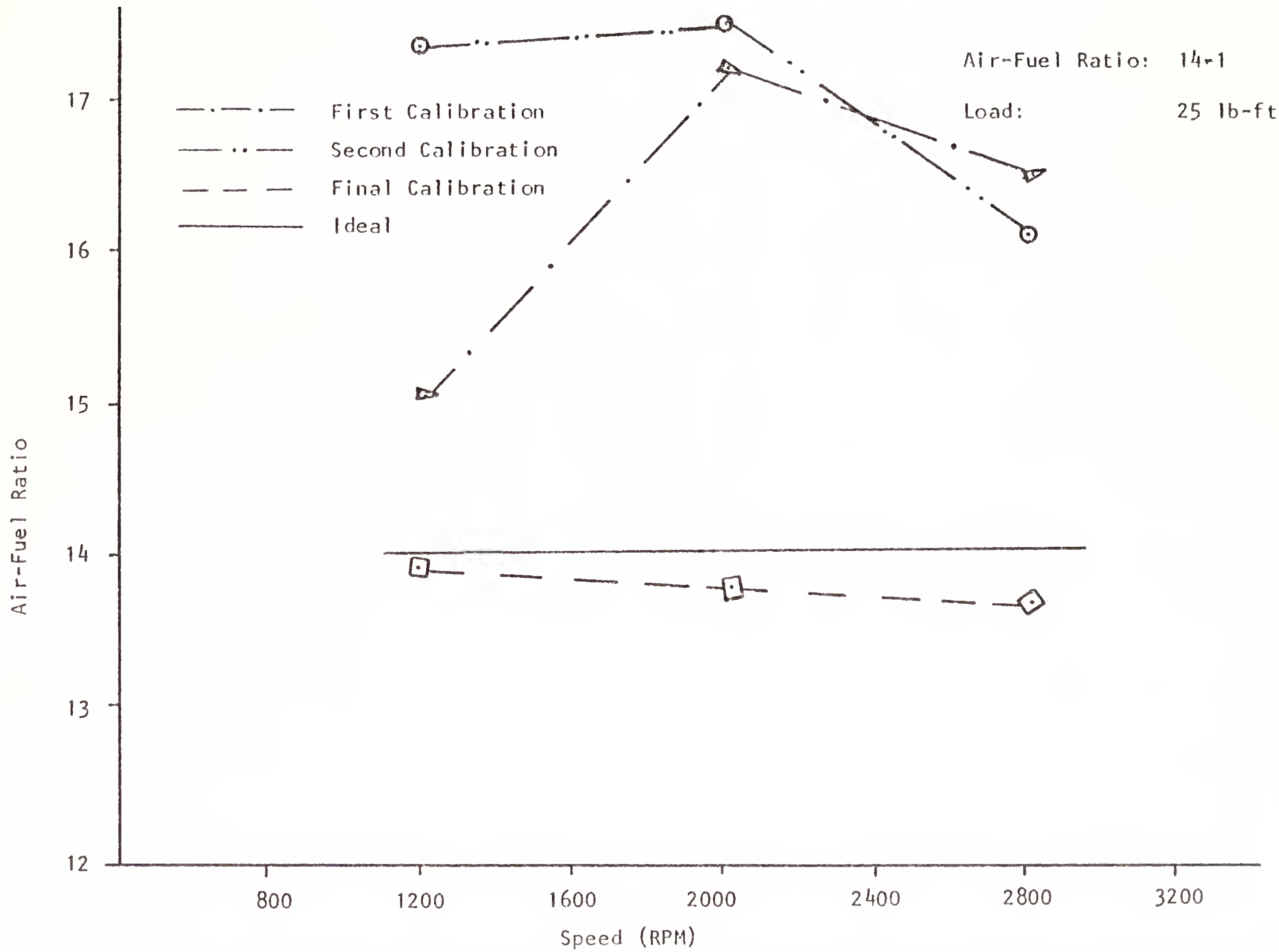


Figure 31. Comparison of the Result of 14-1 Air-Fuel Ratio on 3 Different Calibrations

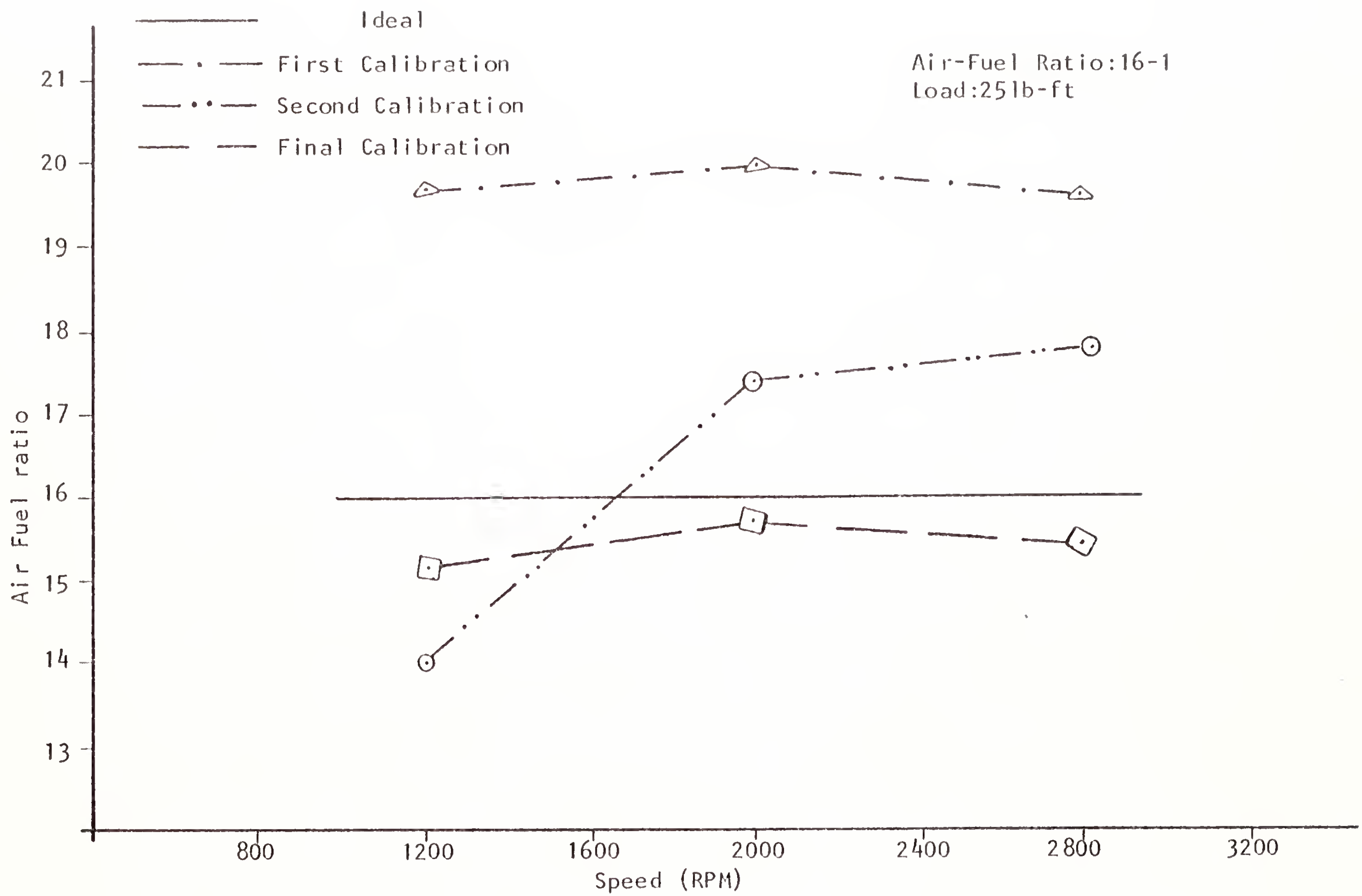


Figure 32. Comparison of the Result of 16-1 Air-Fuel Ratio on 3 Different Calibrations

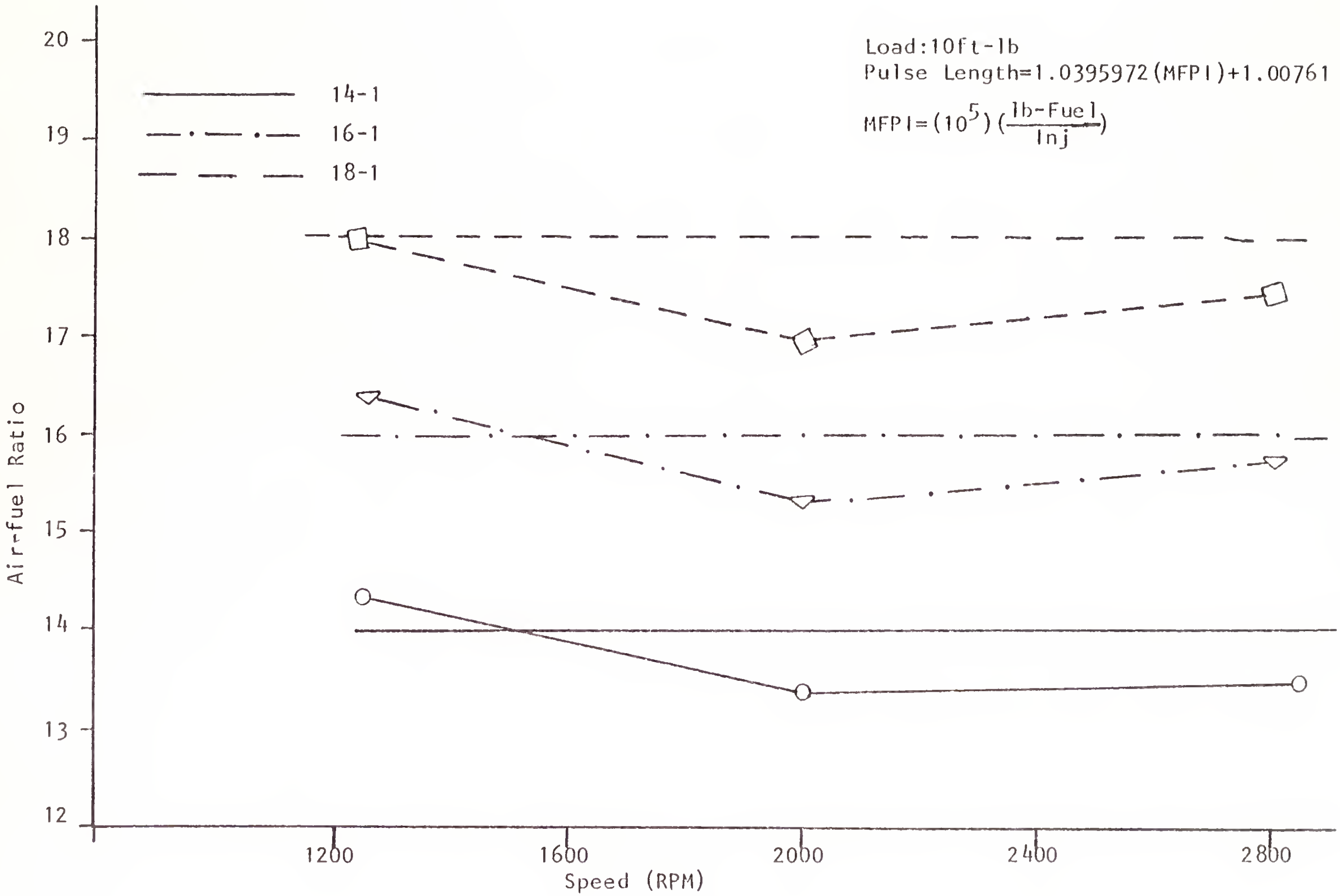


Figure 33. Result of Air-Fuel Ratio for The Final Calibration @ 10 ft-lb

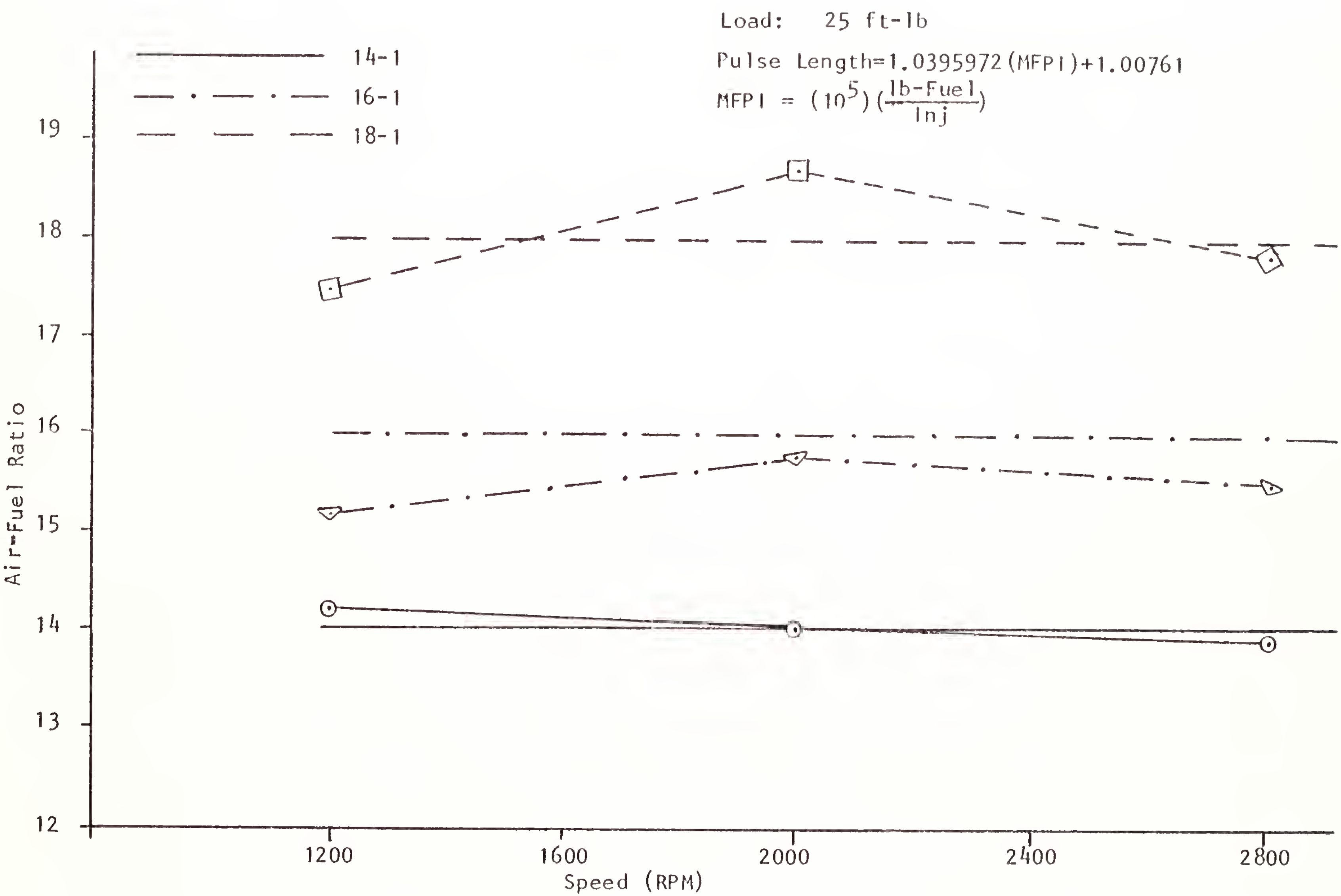


Figure 34. Result of Air-Fuel Ratio for The Final Calibration @ 25 ft-lb

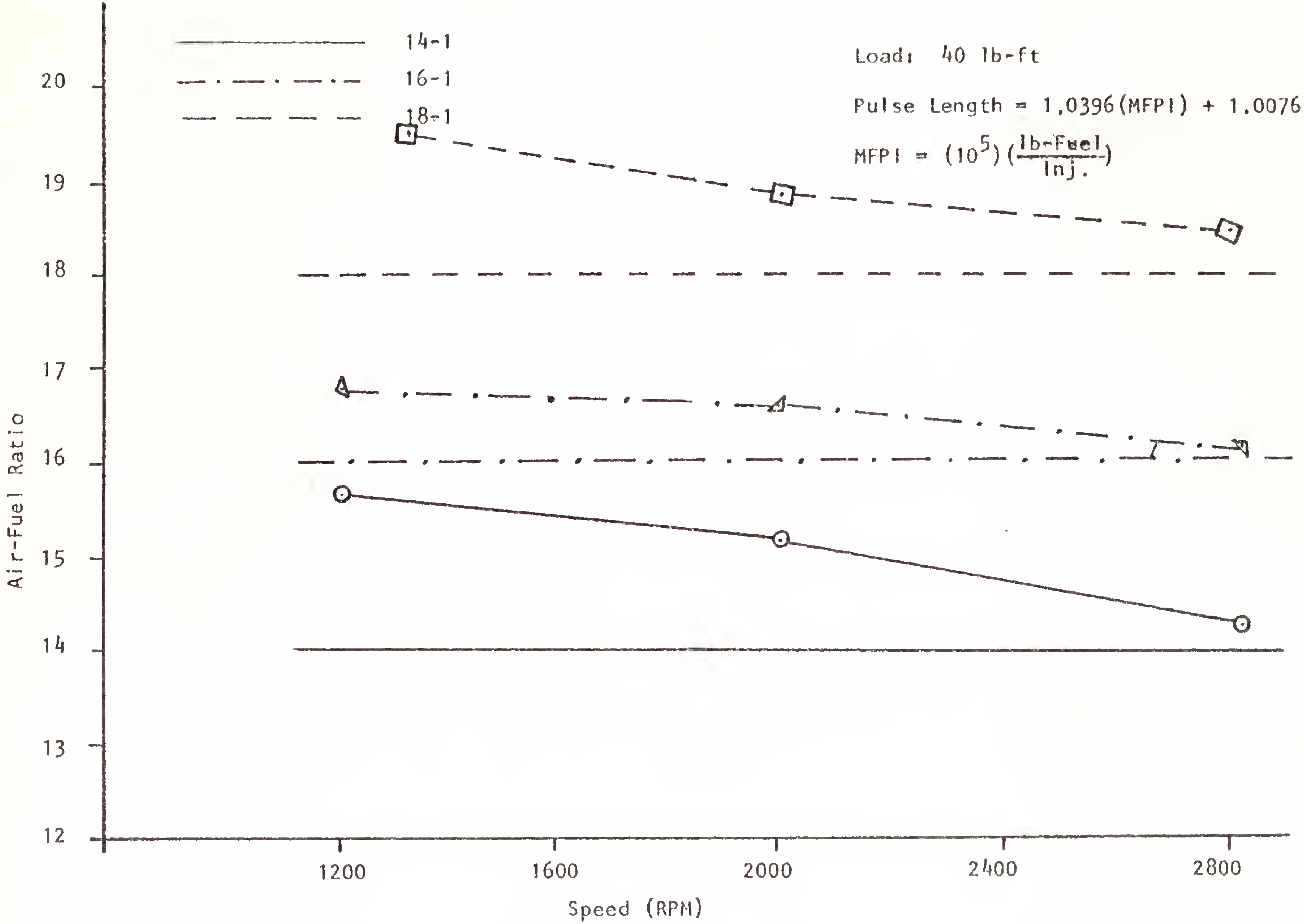


Figure 35. Result of Air-Fuel Ratio for The Final Calibration @ 40 lb-ft

flow since the microcomputer was calculating injection pulses based on the voltage of air flow sensor.

A statistical analysis was performed on the data for the air-fuel ratio controller in which the mean, standard deviation, and percent standard deviation were calculated. The results of this statistical analysis are presented in Table 3. Also a correlation statistical test was done on the linearity of the fuel injector calibration based on the total final data. The result of this analysis as shown in Appendix E proved that the linear calibration was quite accurate. Table 4&5 also provide the statistical analysis on the results of air-fuel ratio for the first two injector calibrations.

To compare the result of this research on air-fuel ratio control with the Bosch system a set of data was taken while the engine was operating on the Bosch system over the range speeds from 1200 to 2800 for the two loads of 25 lb-ft and 40 lb-ft. The results of this test are shown in Figure 36 and Table 6. The data for this test is listed in Appendix H.

6-3 Ignition Timing Control Results

The analysis of the ignition timing controller data is presented in Table 7 and plotted on Figure 37 and 38. Figure 37 shows the measured ignition spark advance value compared to the piecewise linear relationship used in the controller. Figure 38 presents the measured ignition pulse length or ignition dwell compared to the specified value. Both of these tests were taken for six engine speeds over the range of 1000 to 2800 rpm. Each point on these graphs represents the average of a test taken at the indicated speed.

The data and computed results for the ignition control testing are given in Appendix I. Table 7 shows the statistical analysis of this data in which mean, standard deviation and percent standard deviation were calculated for

AIR-FUEL RATIO	RPM	LOAD	TESTED AIR FUEL RATIO MEAN	STANDARD DEVIATION AFR	% STANDARD DEVIATION FROM MEAN AFR	NO TESTS	PERCENT OFFSET
14-1	1200	10	14.26	0.22	1.53	5	1,87
	2000		13.37	0.43	3.23	5	4.50
	2800		13.42	0.33	2.42	5	4.07
	1200	25	13.97	0.10	0.73	5	0.23
	2000		13.99	0.32	2.26	5	0.03
	2800		13.85	0.24	1.77	5	1.07
	1200	40	15.69	0.05	3.22	5	12.04
	2000		15.20	0.59	3.91	5	8.57
	2800		14.26	0.69	4.87	5	1.86
			14.22(Avg.)	0.33(Avg.)	2.65(Avg.)	45(Total)	3.80(Avg.)
16-1	1200	10	16.30	0.33	2.01	5	1.89
	2000		15.40	0.13	0.81	5	3.72
	2800		15.65	0.17	1.10	5	2.19
	1200	25	15.17	0.41	2.69	5	5.21
	2000		15.72	0.22	1.42	5	1.75
	2800		15.50	0.60	3.25	5	3.14
	1200	40	16.82	0.66	3.95	5	5.12
	2000		16.66	0.32	1.94	5	4.13
	2800		16.17	0.67	4.12	5	1.07
			15.92(Avg.)	0.38(Avg.)	2.36(Avg.)	45(Total)	3.13(Avg.)
18-1	1200	10	18.11	0.16	0.91	5	0.62
	2000		17.09	0.39	2.30	5	5.08
	2800		17.52	0.21	1.21	5	2.68
	1200	25	17.42	0.39	7.97	5	3.22
	2000		18.64	0.67	3.61	5	3.58
	2800		17.82	0.31	1.72	5	1.02
	1200	40	19.76	0.85	4.29	5	9.78
	2000		18.90	0.25	1.34	5	5.01
	2800		18.57	0.76	4.09	5	3.20
			18.19(Avg.)	0.55(Avg.)	3.05(Avg.)	45(Total)	3.80(Avg.)

Table 3. Final Results of Air-Fuel Ratio Control

	AIR-FUEL RATIO	LOAD	SPEED RPM	TESTED AIR-FUEL RATIO	STANDARD DEVIATION AFR	% STANDARD DEVIATION	NO. TESTS	PERCENT OFFSET
Injectors Calibration from Ref. 3	14-1	25	1200	15.30	0.91	5.98	5	9.26
			2000	17.46	0.53	3.04	5	24.71
			2800	16.67	0.79	4.76	5	19.09
	16-1	25	1200	19.66	1.18	6.02	5	22.90
			2000	20.08	0.32	1.69	5	25.47
			2800	19.62	1.05	5.34	5	22.61

Table 4. Result of Air-Fuel Ratio Control Using the First Injectors Calibration, (from Ref. 3)

	AIR-FUEL RATIO	LOAD	SPEED RPM	TESTED AIR-FUEL RATIO	STANDARD DEVIATION AFR	% STANDARD DEVIATION	NO. TESTS	PERCENT OFFSET
Injectors Calibration from above data	14-1	25	1200	17.59	0.09	0.54	5	25.63
			2000	17.70	0.79	4.47	5	26.45
			2800	16.38	0.16	1.02	5	17.03
	16-1	25	1200	14.00	0.72	5.10	5	12.47
			2000	17.44	0.91	5.20	5	9.00
			2800	17.77	0.17	0.99	5	9.83

Table 5. Result of the Air-Fuel Ratio Control Using the Second Injectors Calibration (using data from Table 2)

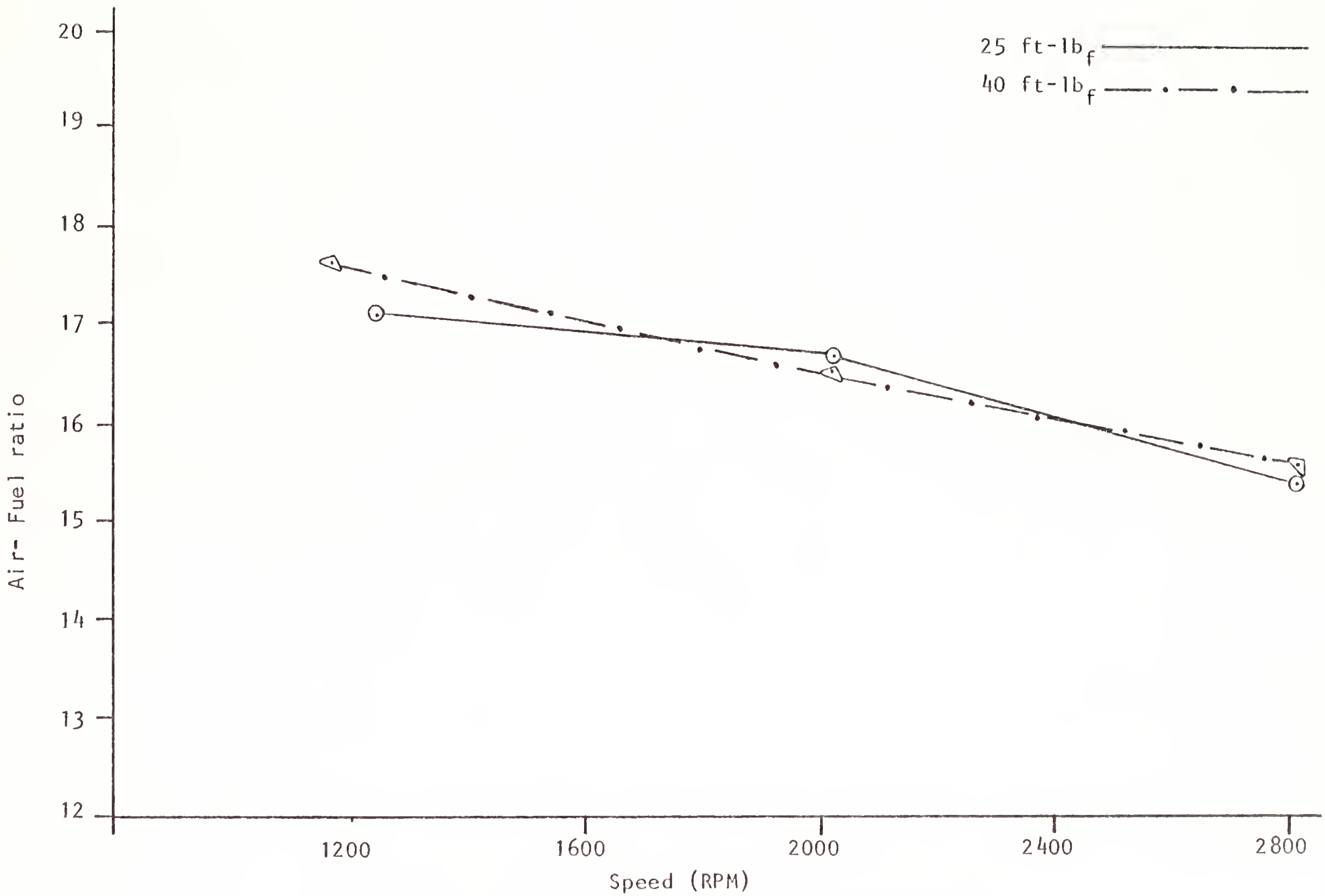


Figure 36. Air-Fuel Ratio vs. RPM for the Bosch system

LOAD LB-FT	SPEED RPM	TESTED AIR-FUEL RATIO	STANDARD DEVIATION AFR	PERCENT STANDARD DEVIATION FROM MEAN	NO. TEST
25	1200	17.57	0.59	3.06	5
	2000	16.80	0.43	2.55	5
	2800	15.56	0.58	3.71	5
40	1200	17.06	0.61	3.60	5
	2000	16.81	0.35	2.10	5
	2800	15.30	0.42	2.79	5

Table 6. Result of Air-Fuel Ratio Using Bosch System

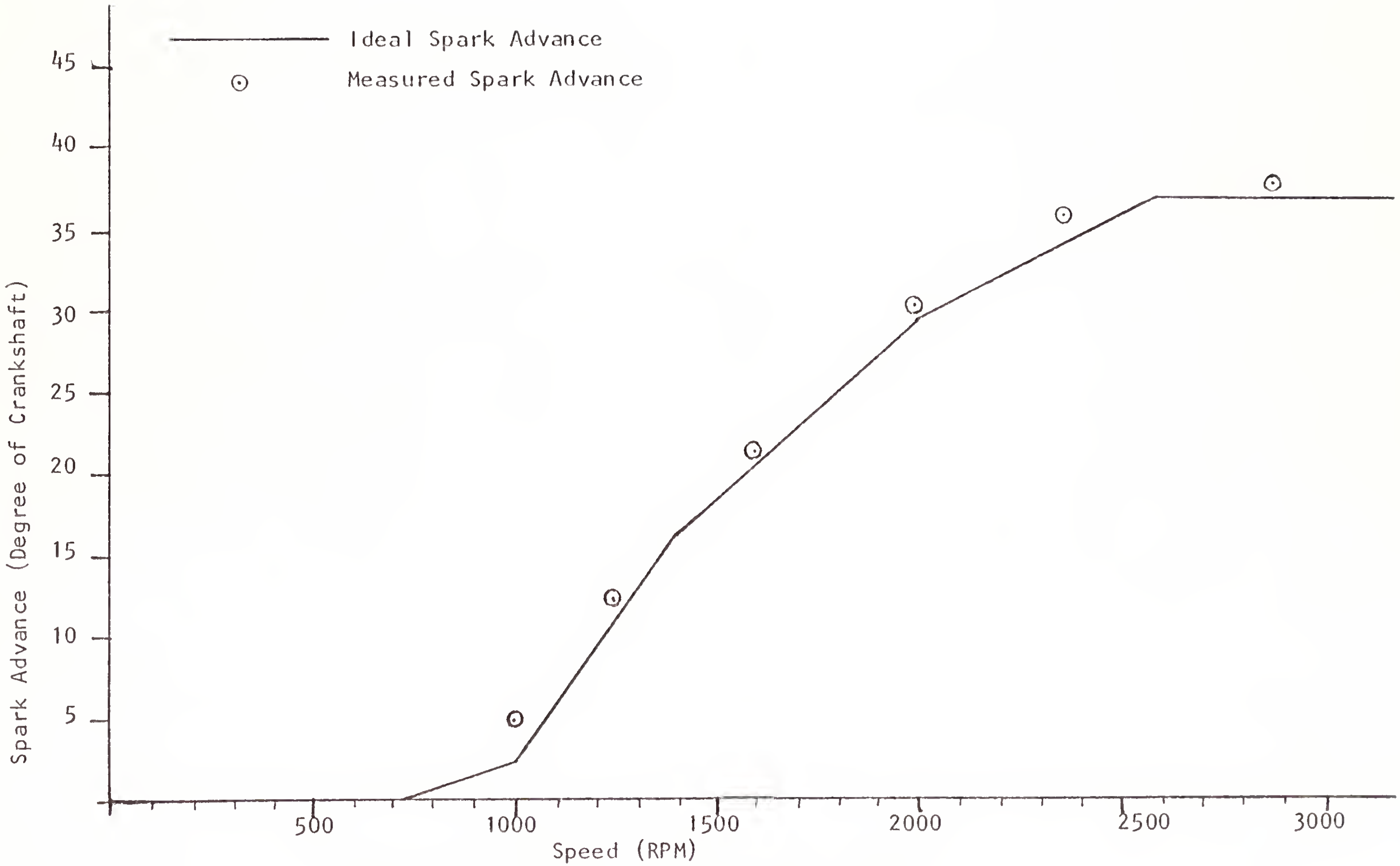


Figure 37. Ignition Spark Advance vs. Speed

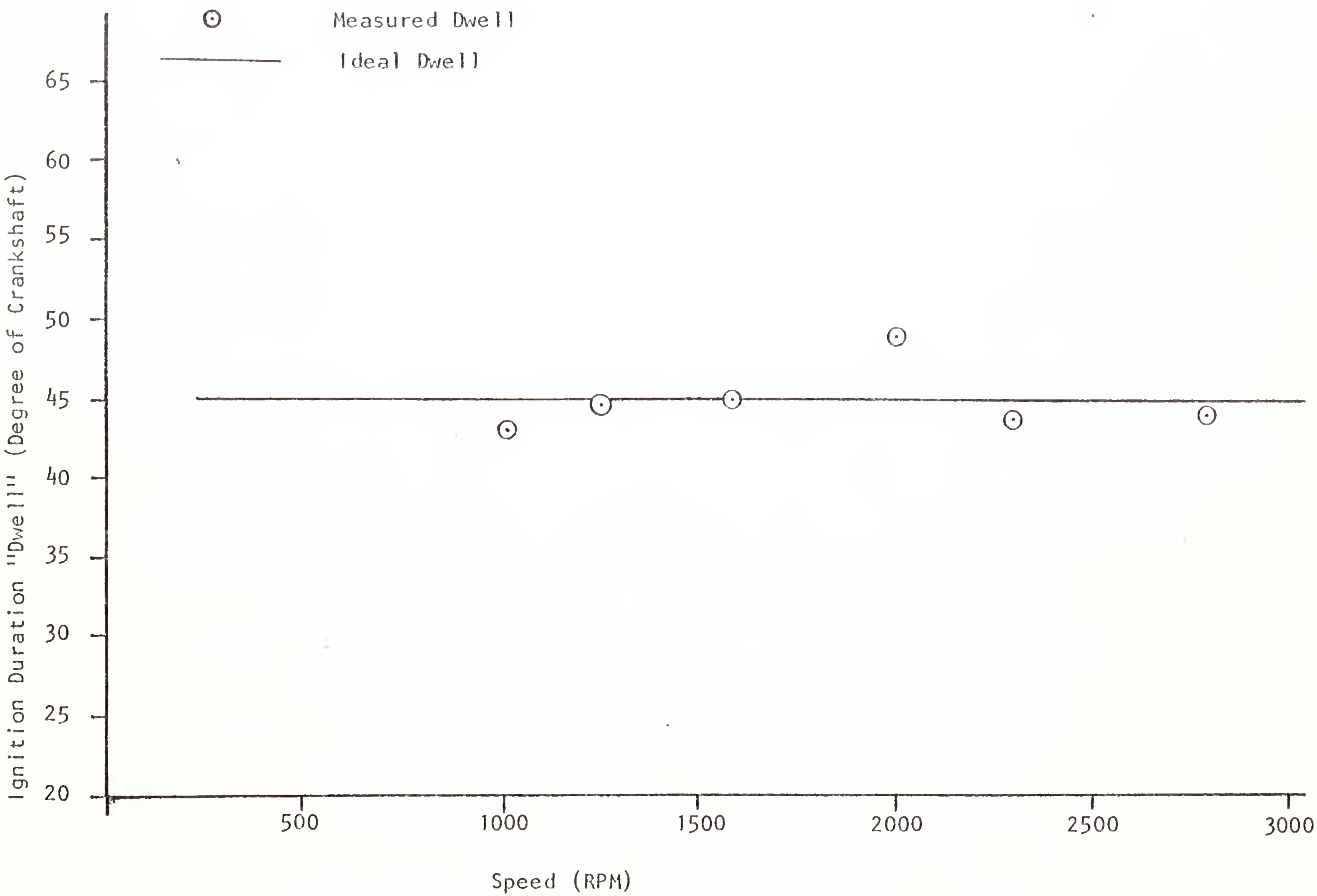


Figure 38. Ignition Pulse Lenght (DWELL) vs. Speed

NO. TESTS	DESIRED SPEED RPM	MEAN SPEED MEASURED DAYTRNIX	MEAN SPARK ADVANCE DEG CS	STANDARD DEVIATION SPARK ADVANCE	% STANDARD DEVIATION FROM MEAN SPARK ADVANCE	IDEAL SPARK ADVANCE °CS	MEAN DWELL DEG CS	STANDARD DEVIATION DWELL	% STANDARD DEVIATION FROM MEAN DWELL	IDEAL DWELL °CS	PERCENT OFFSET SPARK ADVANCE	PERCENT OFFSET DWELL
9	1000	999.4	4.70	1.04	5.19	4.0	43.58	1.180	2.71	45	17.50	3.15
9	1200	1245.5	12.95	1.52	6.10	11.6	44.95	1.320	2.93	45	11.64	0.11
9	1600	1599.3	21.48	0.50	1.35	20.5	45.11	0.817	0.81	45	4.78	0.24
9	2000	2008.0	29.92	1.14	2.51	29.0	48.45	0.726	1.50	45	3.17	7.67
9	2300	2347.8	36.00	1.51	2.95	34.5	43.91	0.572	1.30	45	4.35	2.42
9	2800	2854.4	38.16	2.01	3.90	38.0	43.87	0.762	1.70	45	0.42	2.51
45 (Total)	1816.7 (Avg.)	1842.4 (Avg.)	23.87 (Avg.)	1.29 (Avg.)	3.67 (Avg.)	22.93 (Avg.)	44.97 (Avg.)	0.900 (Avg.)	1.83 (Avg.)	45 (Avg.)	6.98 (Avg.)	2.68 (Avg.)

Table 7. Results of Ignition Timing Control

the spark advance, dwell, and rpm. Uncertainty analysis was made on the ignition timing measurements. The details of this analysis are given in Appendix D. The result of this analysis showed there is a maximum of 3.1 degrees crankshaft limit of error associated with result of the spark advance and 3.08 degrees with the ignition dwell angle.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7-1 Introduction

This chapter will provide a summary of the results and conclusions of this research and recommendations for further study.

7-2 Summary of Results and Conclusions

A microcomputer fuel injection and ignition timing control system was designed and tested on an internal combustion engine over the range of speed from 1000 to 3000 and at loads of 10.0 to 40.0 lb-ft at the three air-fuel ratios of 14-1, 16-1 and 18-1. The ignition spark advance and dwell control system was tested at six speed values: 1000, 1200, 1600, 2000, 2300, and 2800 rpm.

The results of testing the air-fuel ratio controller showed that the ability to maintain a prescribed air-fuel ratio over a range of operating conditions is quite dependent on accurate calibrations of the air flow sensor and the fuel injectors. The ability of the system to produce repeatable results is evidenced by the fact that of the 27 sets of data the percent standard deviation only exceeded 5% on one set. The average percent standard deviation was only 2.7%. The ability of the system to obtain the prescribed air-fuel ratio (which is strongly dependent on the above mentioned calibrations) was not as good. The percent off set exceeded 5% on seven of the 27 sets of data with the average percent offset of 3.58%. The larger errors appeared to occur at the heavier loads at the lower speeds.

The six sets of data taken for the Bosch controller indicated a repeatability of 3% standard deviation, but the value of air-fuel ratio varied by 11 to 12% over the range of speeds tested for each load.

The ignition spark advance controller proved to be successful with the maximum deviation of 1.50 degree of CS from the prescribed advance. The average deviation for the six sets of data was less than 1.00 degree of crank shaft. The repeatability of the system was indicated by the 3.67% average percent standard deviation. The limit of error for the measurement of the spark advance angle was between 0.54 degree crank shaft at 1000 rpm and 3.10 degree of the crank shaft at 2800 rpm.

The ignition dwell angle was maintained constant with a maximum error of 3.5 degrees crankshaft and an average error of 1.2 degrees crank shaft. The dwell angle was repeatable with a 1.83% standard deviation. The uncertainty analysis for the measurements of the dwell angle indicated a limit of error between 1.24 and 3.08 degree crank shaft.

Finally, the floating point arithmetic operations with a 2 byte mantissa and a 1-byte exponential proved to be adequate for computing injection pulse duration and angle of spark advance.

7-3 Recommendations

To control air-fuel ratio, ignition spark advance and ignition dwell angle with greater accuracy, and to improve and expand the system for further research, several recommendations are given in this section as follows:

1. The microcomputer system could be improved by the addition of more input-output ports and programmable interval timers.
2. Improvements could be made on the system by increasing the number of bit on the counters of the speed sensor, ignition spark advance and ignition dwell angle from 12-bit to 16-bit. This would increase the

resolution of these systems to 1 part in 65,000.

3. Fuel injection values had to be adjusted for an 8-bit interval timer with a clock division rate of 64 μ sec count. The resolution of the fuel injection pulse was 164 μs which created an uncertainty in the fuel injection in the order of 3.2%. The source of error could be reduced by using an interval timer with more bits and a faster clock rate. A 16 bit timer would permit use of a 1 mhz clock and reduce this timing uncertainty to less than 0.1%.
4. The average execution times for the multiplication, division, subtraction, and addition routines were 1870 μsec, 1120 μsec, 530μs, and 500 μsec respectively. These routines could be improved for faster operation by a combination of additional hardware and improved software.
5. The fuel measuring system could be improved by changing from a mass measuring to a volumetric measuring system. Also, an automatic timing system could be devised to measure the time for consumption of the prescribed volumn of fuel.
6. The air flow sensor could be improved by replacing the potentiometer with a digital position encoder, or a more reliable potentiometer.
7. The air flow measuring system could be improved by using a smaller nozzle, a pitot static measuring system, or a positive displacement flow measuring device.
8. If more accurate and reliable fuel and air flow measuring systems were provided the air flow sensor and the fuel injectors should be carefully recalibrated.
9. Data for the ignition time controller was collected using the same

sweep rate on the oscilloscope for measuring the cycle of the distributor signal, the spark advance with respect to the distributor signal, and the ignition pulse duration. As a result the ignition pulse duration and the spark advance were small compared to the span of the instrument and the limit of error for these measurements was large. These errors could be reduced if the time base of the oscilloscope were set at the minimum sweep rate for each measurement. The uncertainties that could be obtained are indicated below.

RPM	λ_{ASA} %	UNCERTAINTY ASA DEG CS	λ_{AIGD}%	UNCERTAINTY AIGH DEG CS
1000	18.13	.362	.593	.717
1200	6.55	.589	1.560	.702
1600	4.31	.862	1.52	.684
2000	3.38	.980	1.58	.711
2300	3.04	1.018	1.64	.738
2800	3.01	1.144	1.76	.792

10. The ultimate purpose of the microprocessor control of fuel injection and ignition timing to reduce exhaust emissions and improve economy could be more readily realized if an exhaust emission sensor and a load sensor were provided so the control loop could be closed. This would present a whole new set of opportunities for improved control strategies.

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APPENDIX A

MICROCOMPUTER SPECIFICATIONS

Model	KIM-1 Microcomputer System
Manufacture	MOS Technology, Inc.
Available RAM	1152 bytes
Available ROM	2048 bytes
Available I/O	15 bits
Address Range	65,536 bytes
No. of Addressing Modes	13
MPU	8-Bit, 6502 Microprocessor Array
Available Interval timers	1
Interrupt Mode	Non-Maskable (NMI) and Interrupt Request (IRQ)

Additional Memory

Manufacturer	The Digital Group
Available RAM	8192 bytes

APPENDIX B

ENGINE SPECIFICATIONS

Model	1968 Volkswagen, Electronic Fuel Injection
Number of Cylinders	4
Displacement	96.9 cu. in. (1.584 (it)
Compression Ratio	8.8:1
Torque (SAE)	86.8 ft-lb @ 2800 rpm
Output (SAE)	65 bhp @ 4600 rpm
Valve Clearance	.006 in (.15 mm) intake and exhaust
Ignition Timing	0° (TDC) @ 850 rpm with vacuum hose disconnected
Spark Plug Type	Bosch W 145 T 1
Engine Oil	SAE 30 (MS) between 40°F and 86°F
Bore	3.36 in (85.5 mm)
Stroke	2.72 in (69.0 mm)

Electronic Ignition System Specification*

Manufacture	Borg Warner
Triggering Means	Infra-red emitting diode and photo-transistor receiver
Timing Accuracy	Up to 1/4 of 1 degree
Current Rating	10 Ampers
Operating Voltage	12 Volts I 6 volts, negative ground

* This system replaced breaker point and condensor in the distributor.

APPENDIX C

TESTING EQUIPMENT SPECIFICATION

	EQUIPMENT	SPECIFICATION
1.	Oscilloscope	Tektronix Type S64 with Time Base Type 2B67
2.	Daytronic Modular Instrument System	Daytronic Models: 840, 870, 862, and 821
3.	Electronic Counter for measuring time for fuel consumption	Hewlett Packard Model 523D
4.	Electronic Counter for measuring injection pulse time	Universal EPOT Model 6146 with Timer Model 602
5.	Strain Guage Transducer for load measurement	Transducer Model BTC-FF63-CS-50
6.	Analog to Digital Convertor	Analog Device, Model ADC-10Z
7.	Water Micro Manometer	Meriam, Type MICRO, Model 34FBZ
8.	Mass Balance	Detecto Gram Balance
9.	Digital Multimeter	Fluke Multimeter Model 8000A
10.	D-C Power Supplies	LAMBDA Dual Model LPD-421A-FM

APPENDIX D

UNCFRTAINTY ANALYSIS

In order to assess the value of the results of this work it is necessary to evaluate the uncertainty associated with each result. These uncertainties are calculated by the proceedure presented by Spargue and Nash (25). For a variable H which is a function of various independently measured values of $Y_1, Y_2, Y_3, \ldots, Y_n$ or

$$H = f\,(Y_1, Y_2, Y_3, \ldots, Y_n), \tag{1}$$

the uncertainty in H is calculated from the equation

$$\lambda H = S_1^2 \ \lambda_1^2 + S_2^2 \ \lambda_2^2 + S_3^2 \ \lambda_3^2 + \ldots + S_n^2 \ \lambda_n^2 \tag{2}$$

where

$$S_n = \frac{\partial f}{\partial Y_n} \ \frac{Y_n}{H} \tag{3}$$

and λ_n is the uncertainty in the n'th measured value in percent of reading. There are two factors which contribute to the uncertainty of each measurment. The first is the ability of the instrument to position the indicator in the correct position on the scale. This is called instrument uncertainty, The second is the ability of the experimenter to accurately read the indicated value which is known as a resolution uncertainty. Manufacturer's specifications ususally indicate the instrument uncertainty. In the absence of better information from manufacture's literature, resolution and instrument uncertainties will both be assumed equal to Y_z of the smallest scale division of the instrument's display.

The uncertainties in the ignition timing parameters of spark advance and dwell will be calculated in this Appendix. The uncertainties in air-flow sensor's calibration, air-fuel ratio calculation, and fuel injector calibration will be summarized. These uncertainties are calculated in Appendix C of the reference 3.

Ignition Spark Advance Uncertianty

The angle of spark advance in degree of crank shaft is calcualted from the equation:

$$ASA = \frac{(SPADIS)360}{HADIST} - \phi \text{ deg} \tag{4}$$

where SPADIS is the measured phase difference between the ignition pulse and the distributor signal in units of time, ϕ is the phase shift between the distributor and crank shaft cycle in angular degrees of the crank shaft, and HADIST is one half of the period of the distributor signal in unit of time. To calculate the uncertainty in ASA the uncertainties in SPADIS, ϕ and HADIST must first be calculated. The phase shift ϕ was measured in units of time and converted to degree of crank shaft by the equation:

$$\phi \text{ (deg. of crank shaft)} = \frac{(\phi \text{ time})\ (360)}{HADIST}\ . \tag{5}$$

The variables ϕ (time), HADIST, and SPADIS were measured with the Taktronix Type 564 Storage Oscilloscope equipped with a type 2B67 Time-Base Plug in unit. Specifications for this instrument indicate that the calibrated sweep rates are within 3% of the step switch setting. Resolution accuracy will be taken as 1/2 the smallest scale division.

To measure ϕ (time), as explained in Chapter 5, the engine was run at the speed of 850 rpm with vacuum nose off. The values of HADIST, ϕ_t and ϕ_{deg} were 70 ms, 3 ms and 15.43 deg respectively, and the uncertainties in ϕ_t and HADIST are:

$$\lambda_{\phi t} = (\lambda)^2 \text{ linearity} + (\lambda)^2 \text{ resolution}$$

$$= (3.0)^2 + (\frac{0.1\ 100}{6.0})^2$$

$$= 3.43\%$$

$$\lambda_{HADIST} = (\lambda)^2 \text{ linearity} + (\lambda)^2 \text{ resolution}$$

$$= (3.0)^2 + (\frac{100}{70})^2$$

$$= 3.323\%$$

The sensitivities of ϕ deg with respect to ϕ_t and HADIST can be computed from equations 3 and 5 as follow:

$$S_{\phi t} = \frac{\frac{\partial \phi \text{ deg}}{\partial \phi_t} \phi_t}{\phi_{deg}} = 1$$

$$S_{HADIST} = \frac{\frac{\partial \phi_{deg}}{\partial HADIST} (HADIST)}{\phi_{deg}} = 1.$$

The uncertainty in ϕ_{deg} is calculated from equation 2.

$$\lambda_{\phi deg} = (\lambda)^2_{\phi t} (S)^2_{\phi t} + (\lambda)^2_{HADIST} (S)^2_{HADIST}$$

$$= (3.430)^2 (1)^2 + (3.323)^2 (1)^2$$

$$= 4.78\%$$

The uncertainties in SPADIS, HADIST, and ASA in equation 4 depend on the rpm of engine and angle of spark advance. The calculation of the uncertainties of the average of 9 measurements of these parameters for a speed of 1000 rpm is as follow:

$$\lambda_{SPADIS} = (\lambda^2) \text{ linearity} + (\lambda^2) \text{ resolution}$$

$$= (3.0)^2 + (\frac{10.}{.66})^2$$

$$= 15.45\%$$

$$\lambda_{\overline{SPADIS}} = \frac{\lambda SPADIS}{m} = \frac{15.45}{9} = 5.15\%$$

$$\lambda_{HADIST} = (\lambda^2)\text{ linearity} + (\lambda^2)\text{ resolution}$$

$$= (3.0)^2 + (\frac{100}{58})^2 = 3.46\%$$

$$\lambda_{\overline{HADIST}} = \frac{\lambda_{HADIST}}{m} = \frac{3.46}{9} = 1.153\%$$

The sensitivity of ASA with respect to SPADIS is computed from equations 3 and 4,

$$S_{SPADIS} = \frac{\frac{\partial ASA}{\partial SPADIS}\ SPADIS}{ASA}$$

$$= \frac{\frac{360}{HADIST}\ SPADIS}{\frac{(SPADIS)(360)}{HADIST} - \phi_{deg}}$$

$$= \frac{1}{1 - \frac{(HADIST)(\phi deg)}{(SPADIS)(360)}} .$$

Likewise, the sensitivity of ASA with respect to HADIST and ϕ deg will be:

$$S_{HADIST} = \frac{\frac{\partial ASA}{\partial HADIST}\ HADIST}{ASA}$$

$$= \frac{-\frac{(SPADIS)(360)}{(HADIST)^2} HADIST}{\frac{(SPADIS)(360)}{HADIST} - \phi\ deg}$$

$$= \frac{-1}{1 - \frac{(HADIST)(\phi_{deg})}{(SPADIS)(360)}}$$

and

$$S_{\phi_{deg}} = \frac{\frac{\partial ASA}{\partial \phi_{deg}}\ \phi_{deg}}{ASA}$$

$$= \frac{(-1)(\phi_{deg})}{\frac{(SPADIS)(360)}{HADIST} - \phi\ deg}$$

$$= \frac{1}{1 - \frac{(SPADIS)(360)}{(HADIST)(\phi_{deg})}} .$$

The average values of SPADIS and HADIST for 9 different readings at engine speed of 1000 rpm are:

$\overline{SPADIS} = 3.3$ ms,

$\overline{HADIST} = 58$ ms,

$m = 9$.

The values of the sensitivities are:

$S_{SPADIS} = 4.05\%$

$S_{HADIST} = 4.05\%$

$S_{\phi_{deg}} = -3.54\%$

Finally, the uncertainty in ASA will be:

$$\lambda_{ASA} = (\lambda^2)_{\phi_{deg}} (S^2)_{\phi_{deg}} + (\lambda^2)_{SPADIS} (S^2)_{SPADIS} + (\lambda^2)_{HADIS} (S^2)_{HADIS}$$

$$= (4.78)^2 (3.54)^2 + (5.15)^2 + (4.054)^2 + (1.153) (4.054)^2$$

$$= 27.26\%.$$

The uncertainty in ASA in angular degrees of crank shaft was calculated to be .545 deg.

The uncertainties in angle of spark advance was also computed for speeds of 1200, 1600, 2000, 2300, and 2800 rpm by the same technique. The result of these calculations are given in Table 1.

Ignition Dwell Uncertainty

The angle of the Ignition Dwell was calculated from the ignition pulse duration from equation:

$$AIGD = \frac{(IGPU)(360)}{HADIST} \tag{6}$$

Table 1 Results of Uncertainty in Angle of Spark Advance

Speed rpm	SPADIS MS	HADIST MS	ϕ_d deg. CS	λ_{ϕ_d} %	S_{ϕ_d}	λ_{HADIST} %	S_{HADIST}	λ_{SPADIS} %	S_{SPADIS}	λ_{ASA} %	UNCERTAINTY deg of CS
1000	.66x5 3.3	5.8x10 58	15.43	4.78	-3.540	1.15	-4.054	5.15	4.05	27.26	.545
1200	.75x5 3.75	9.52x5 47.6	15.43	4.78	-1.193	1.06	-2.19	4.56	2.19	11.73	1.056
1600	.768x5 3.84	7.52x5 37.6	15.43	4.78	- .723	1.09	-1.723	4.45	1.723	8.62	1.723
2000	.751x5 3.755	5.94x5 29.72	15.43	4.78	- .513	1.15	-1.513	4.55	1.513	7.51	2.178
2300	.73x5 3.65	5.12x5 25.58	15.43	4.78	- .429	1.19	-1.429	4.67	1.429	7.18	2.410
2800	.614x5 3.07	4.1x5 20.5	15.43	4.78	- .401	1.29	1.40	5.52	1.40	8.16	3.100

where IGPU is the duration of ignition pulse and HADIST is one half of the distributor cycle, where both were measured by the Tektronix Type 564 storage Oscilloscope. Also, AIGD is defined to be the angle of ignition dwell in the units of degree of crank shaft. In order to compute uncertainty in AIGD uncertainties in IGPU and HADIST must first be calculated. The compulation of uncertainty in AIGD for a speed of 1000 rpm is shown. The results for 1200, 1600, 2000, 2300, and 2800 rpm is presented in Table 2.

$$\lambda_{HADIST} = (\lambda)^2_{Resolution} + (\lambda)^2_{Linearity}$$

$$= (3.0) + \frac{100}{58}^{2} = 3.46\%$$

$$\lambda_{\overline{HADIST}} = \frac{\lambda HADIST}{m} = \frac{3.46}{9} = 1.153\%$$

$$\lambda_{IGPU} = (\lambda)^2_{Resolution} + (\lambda)^2_{Linearity}$$

$$= (3.0)^2 + \frac{10.}{1.456}^{2} = 7.49\%$$

$$\lambda_{\overline{IGPU}} = \frac{\lambda IGPU}{m} = \frac{7.49}{m} = 2.50\%$$

The sensitivities of AIGD to HADIST and IGPU will be calculated from equations 3 and 6 as follow:

$$S_{HADIST} = \frac{\frac{\partial AIGD}{\partial HADIST}(HADIST)}{AIGD}$$

$$= \frac{-\frac{(IGPU)(360)}{(HADIST)^2}(HADIST)}{\frac{(IGPU)(360)}{(HADIST)}} = -1$$

$$S_{IGPU} = \frac{\frac{\partial AIGD}{\partial IGPU}(IGPU)}{AIGD}$$

$$= \frac{\frac{360}{HADIST}(IGPU)}{\frac{(IGPU)(360)}{HADIST}} = 1$$

The uncertainty in AIGD can now be calculated from equation 2 as:

$$\lambda_{AIGD} = (S^2\lambda^2)_{HADIST} + (S^2\lambda^2)_{IGPU}$$
$$= (1.153)^2(-1)^2 + (2.5)^2\ (1)^2$$
$$= 2.75\%.$$

From this result the uncertainty in degree angle of ignition dwell is 1.24 deg. C.S.

Air Flow Sensor Calibration Uncertainty

The following uncertainties are calculated in reference 3. For the air flow sensor:

$\lambda_{TDB} = 0.862\%$, $\lambda_{TWB} - 1.040\%$, $\lambda_{ATMPR} = 0.0493$

$\lambda_{DENAIR} = 0.86\%$, $\lambda_{PMN} - 2.95\%$, $\lambda_{CFM} = 1.54\%$

and the sensitivity for above parameters are:

$S_{TDB} = 0.998$, $S_{TWB} = -0.0098$, $S_{ATMPR} = 1.010$

$S_{DENAIR} = 1$, $S_{PMN} = 1$, $S_{CFM} = 1$.

From the above values the uncertainty in AMFR is 1.76% and uncertainty in measuring the air flow sensor voltage with the Fluke digital multimeter is 1.43%.

Fuel Injector Calibration Uncertainty

To compute the uncertainty in the calibration of the Fuel Injectors the following uncertainties and sensitivities are used:

$\lambda_{DELGAS} = 1.77\%$, $\lambda_{DELTIM} = 0.043\%$, $\lambda_{RPM} = 0.473\%$

$_{DELGAS} = 1$, $S_{ELTIME} = -1$, and $S_{RPM} = -1$

From the above values the uncertainty in INJECT was computed to be 1.77%. Also, the uncertainty in measuring injection pulse length using the Tektronix Storage Oscilloscope was computed to be 3.83%.

Table 2. Results of Uncertainty in Ignition Dwell Angle

Speed rpm	IGPU ms	HADIST ms	λ_{IGPU}	S_{IGPU}	λ_{HADIST}	S_{HADIST}	λ_{AIGD}	Uncertainty deg C.S.
1000	1.456x5 7.28	5.8x10 58	2.50	1	1.15	-1	2.75	1.24
1200	1.1912x5 5.956	9.52x5 47.60	2.97	1	1.06	-1	3.16	1.42
1600	0.942x5 4.711	7.52x5 37.6	3.68	1	1.09	-1	3.84	1.73
2000	0.8x5 4.0	5.94x5 29.72	4.28	1	1.15	-1	4.43	1.99
2300	0.624x5 3.12	5.12x5 25.58	5.43	1	1.19	-1	5.56	2.50
2800	0.502x5 2.51	4.1x5 20.5	6.71	1	1.29	-1	6.84	3.08

Air-Fuel Ratio Uncertainty

To compute uncertainty in AIRIN, uncertainties and sensitivities in several parameters are calculated first.

uncertainties are:

λ_{TDB} = 0.907%, λ_{TWB} = 1.122%, λ_{ATMPR} = 0.0492%

λ_{DENAIR} = 0.90%, λ_{PMN} = 2.36%, λ_{PNSD} = 2.53%

λ_{CFM} = 1.27%, λ_{AMFR} = 1.56%, $\lambda_{COUNTER}$ = 0.022%

$\lambda_{DELTIME}$ = 2.9%

and the corresponding sensitivities are:

S_{TDB} = -0.989, S_{TWB} = -0.0091, S_{ATMPR} = 1.008, S_{PMN} = 1

S_{DENAIR} = 1, S_{PNSD} = 0.5014, S_{CFM} = 1, S_{AMFR} =1

S_{AMFR} =1, $S_{COUNTER}$ =1, and $S_{DELTIME}$ =1.

From the listed value the uncertainty in AIRIN was calculated to be 3.29% and sensitivity of AIRIN with respect to air-fuel ratio is +1. Also, the uncertainty in measuring 0.4 lb weight of fuel which was used for the determination of DELGAS was calculated to 0.062%, and the sensitivity in DELGAS with respect to air-fuel ratio is 1. Finally, from the above information the uncertainty in air-fuel ratio is:

$$\lambda_{AFR} = (S^2\lambda^2)_{AIRIN} + (S^2\lambda^2)_{DELGAS}$$

$$= (3.29)^2 (-1)^2 + (0.062)^2 (1)^2$$

$$= 3.29\%.$$

APPENDIX E

STATISTICAL ANALYSIS FOR FUEL INJECTOR CALIBRATIONS

To determine how well the fuel injector calibration is compared to a linear relation, statistical analysis is done on 27 points of data collected for the air-fuel ratio controller with the final injector calibration. The mass of fuel per injection and injection pulse duration for these 27 points are as follow:

Injection Pulse (ms)	3.28	3.12	3.06	3.04	2.87	2.81	3.14	2.72	2.74
Mass of fuel/injection $\times 10^5$	2.09	1.99	2.12	1.94	1.77	1.83	1.85	1.70	1.73
Injection Pulse (ms)	4.34	3.89	4.15	3.84	3.54	3.64	3.72	3.69	3.63
Mass of fuel/injection $\times 10^5$	2.97	2.69	2.93	2.69	2.41	2.64	2.55	2.51	2.47
Injection Pulse (ms)	5.13	5.14	5.17	4.82	4.73	4.73	4.66	4.51	4.46
Mass of fuel/injection $\times 10^5$	3.53	3.58	3.93	3.46	3.40	3.56	3.26	3.13	3.12

Let x = injection time (ms)

y = mass of fuel per injection $\times 10^5$

then

$$\bar{x} = 3.873$$

$$\bar{y} = 2.661$$

$$S_{yy} = \sum_{i=1}^{27} (Y_i - \bar{Y})^2 = 11.831$$

$$S_{xx} = \sum_{i=1}^{27} (x_i - \bar{x})^2 = 16.724$$

$$S_{xy} = \sum_{i=1}^{27} (x_i - \bar{x})(Y_i - \bar{Y}) = 13.918$$

$$S^2_{y.x} = \frac{S_{yy} - \frac{S_{xy}^2}{S_{xx}}}{n-2} = .00992$$

$$R^2 = \frac{S^2xy/Sxx}{Syy} = .97905$$

The equation of a straight line is :

$$Y - a + b\ (x - \bar{x})$$

where

$$a = \bar{Y} = 2.6614$$

and

$$b = \frac{Sxy}{Sxx} = .832.$$

therefore, the linear relation between injection pulse duration and mass of fuel per injection is:

$$Y - 0.8322\ x - 0.5617.$$

To obtain the confidence bound for the graph of the above relation the 95% confidence interval of μ_x for three points x=2.50, 3.50, 4.50 is calculated using the relation:

$$\mu_x = \bar{Y}_x \pm S_{\bar{y}.x}\ t_{x12,\ n-2}$$

where $t_{x12,\ n-2}$ is 2.05 for x - .05 and n - 27

$$\bar{Y}_{2.5} = 1.519,\ \bar{Y}_{3.5} = 2.351,\ \bar{Y}_{4.5} = 3.183$$

and

$$S_{\bar{y}.x} = S_{y.x}\ \frac{1}{n} + \frac{(x-\bar{x})^2}{S_{xx}}.$$

From this relation

$$S_{\bar{y}.2.5} = 0.0385,\ S_{\bar{y}.3.5} = .02120,\ S_{\bar{y}.4.5} = .02451$$

thus the result for μ_x will be

$$1.440 < \mu_{2.5} < 1.598$$

$$2.297 < \mu_{3.5} < 2.385$$

$3.113 < \mu_{4.5} < 3.214$

The confidence bounds and graph for the equation of the line are ploted in Figure E-1. This statistical analysis showed the relation between injection pulse duration and mass of fuel per injection is linear with R=.9895.

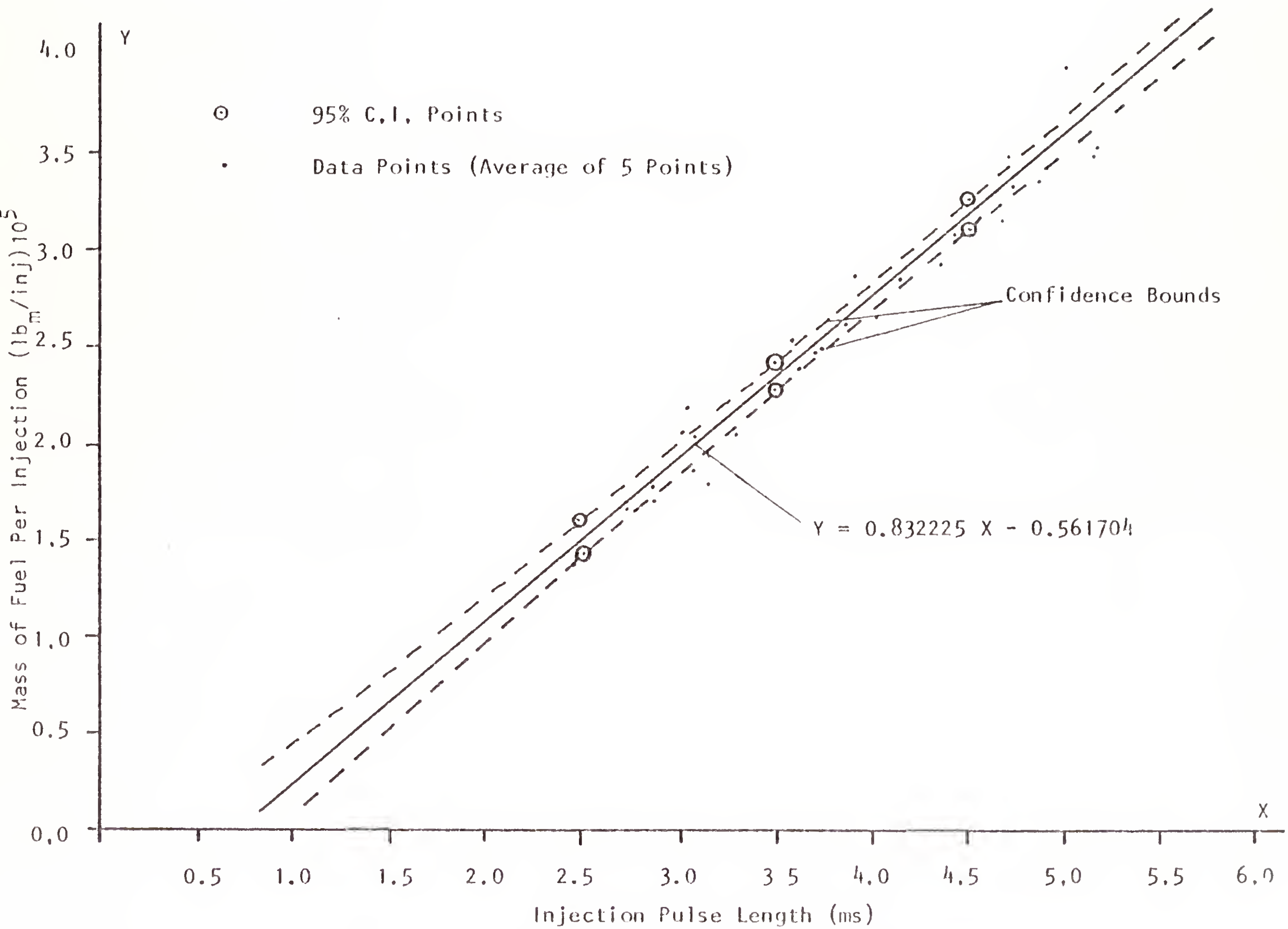

Figure E1. Injection Calibration Confidence Bounds

APPENDIX F

MICROCOMPUTER PROGRAM LISTING

LIST OF PROGRAMS AND SUBROUTINES

0200-024F, 02C4-0360	Initialization program
0250-02C3	Injection program
2000-213F	Multiply
2140-224F	Addition
2300-23EF	Conversion of Air-flor voltage to mass of air per minute
2400-2486	Conversion of mass of fuel per injection to injection time
2490-24C3	Display
24D0-24F4	Conversion of 1/2(RPM) to RPM
2500-2582	Division
25B0-25CF	Subtraction
25D0-26CF	Spark advance program
2700-277F	Ignition time program
2790-283F	Interrupt program
2900-2A38	Data recording program

ZERO PAGE MEMORY MAP

0001-0009	Multiply registers
000A-0018	Divide registers
0019-001C	Constants for ignition system
001D-001F	Ignition time
0020-002B	Intermediate multiply registers
002C-002E	Adjusted RPM with Exp of (-3)
0030-0038	Addition registers
0039-003F	Constants for 180 deg. and $\frac{10^6}{48}$
0040-0045	Intermediate addition registers
0047-007B	Constants for injection system
007C-007E	Unscaled speed register (reading)
0081-0083	Voltage of Air-flow Sensor (reading)
0084-0085	Adjusted Ignition time
0086-0088	Mass of air per minute (scaled)
0089-008B	Result of 1/2 (RPM)
008C-008E	RPM Result
008F-00AC	Constants for Spark Advance
00AD-00AF	Spark Advance Result
00B9-00B2	Mass of fuel per injection
00B3-00B5	Injection time
00EE	Injection time adjusted

Zero Page Memory addresses not used:

002F, 0046, 007F, 0080, 00B6-00ED

LIST OF CONSTANTS

	ADDRESS	VALUE	HEX NO.	DECIMAL NO.	USED FOR
1.	0019 001A 001B	00 50 F4	5000, F4	5.00	Delay for spark advance
2.	0039 003A 003B	00 53 F9	5300, F9	166.00	Ignition spark angle
3.	003C 003D 003E	61 51 00	5161, 00	$10^6/48$	Scaling ignition time
4.	0047 0048 0049	00 20 F2	2000, F2	0.50	RPM Conversion
5.	004A 004B 004C	F5 68 FØ	68FS, FØ	0.41	Conversion from voltage of Air-Flow Sensor to mass of air per minute
6.	004D 004E 004F	96 A8 FØ	A896, FØ	-.34146	Conversion from Voltage of Air Flow Sensor to mass of air per minute
7.	0051 0052 0053	EB 51 FØ	51EB, FØ	.320	Conversion from Voltage of Air-Flow Sensor to mass of air per minute
8.	0054 0055 0056	00 58 F1	5800, F1	.6875	Conversion from voltage of Air-Flow Sensor to mass of air per minute
9.	0057 0058 0059	1F 45 F2	451F, F2	1.08	Conversion from voltage of Air-Flow Sensor to mass of air per minute
10.	005A 005B 005C	EC 95 F3	95EC, F3	-3.315	Conversion from voltage of Air-Flow Sensor to mass of per minute

	ADDRESS	VALUE	HEX NO.	DECIMAL NO.	USED FOR
11.	005D 005E 005F	E1 5A F0	5AE1, F0	.335	Conversion from voltage of Air-Flow Sensor to mass of air per minute
12.	0060 0061 0062	88 42 F2	4288, F2	1.0396	Calibration of injection time First try 7C68, F1 = .972 Second try 64F1, F3 = .788
13.	0063 0064 0065	7C 40 F2	407C, F2	1.0076	Calibration of injection time First try 50F9, F1 = .61489 Second try 631B, F2 = 1.54854
14.	0066 0067 0068	A8 61 02	61A8, 02	10^5	Mass of fuel per injection scaling factor
15.	0069 006A 006B	00 7D F5	7000, F5	15.625	Scaling injection time
16.	006C 006D 006E	dF 46 F2	46dF, F2	1.107407	Scaling speed (RPM)
17.	0070 0071 0072	25 49 EE	4925, EE	1/14	Air-fuel ratio 14-1
18.	0073 0074 0075	00 40 EE	4000, EE	1/16	Air-fuel ratio 16-1
19.	0076 0077 0078	C7 71 ED	71C7, ED	1/18	Air-fuel ratio 18-1
20.	0079 007A 007B	66 66 ED	6666, ED	1/20	Air-fuel ratio 20-1

	ADDRESS	VALUE	HEX NO.	DECIMAL NO.	USED FOR
21.	008F 0090 0091	89 41 EB	4189, EB	.008	Spark advance computation
22.	0092 0093 0094	00 60 F4	6000, F4	6	Spark advance computation
23.	0095 0096 0097	AE 47 ED	47AE, ED	.035	Spark advance computation
24.	0098 0099 009A	00 42 F7	4200, F7	33	Spark advance computation
25.	009B 009C 009D	BF 58 EC	58BF, EC	.021667	Spark advance computation
26.	009E 009F 00A0	A8 72 F5	72A8, F5	14.3335	Spark advance computation
27.	00A1 00A2 00A3	E1 7A EB	7AE1, EB	.015	Spark advance computation
28.	00A4 00A5 00A6	00 40 F2	4000, F2	1	Spark advance computation
29.	00A7 00A8 00A9	00 4C F7	4C00, F7	38	Spark advance computation

INITIALIZATION PROGRAM

Address	Op Code	Operands Byte 1	Operands Byte 2	Mnemonic	Comment
0200	A2	FF		LDX	initialize stack pointer
0202	9A			TXS	
0203	78			SEI	set interrupt disable flag
0204	A9	7F		LDA	define data direction register B
0206	8D	01	17	STA	
0209	A9	00		LDA	define data direction register A
020B	8D	03	17	STA	
020E	D8			CLD	specify the binary mode
020F	A9	85		LDA	specify IRQ vector, low byte
0211	8D	FE	17	STA	
0214	A9	27		LDA	specify IRQ vector, high byte
0216	8D	FF	17	STA	
0219	EA			NOP	
021A	EA			NOP	
021B	A9	44		LDA	initialize speed for 2000 rpm = 4144,E6
021D	85	7C		STA	
021F	A9	41		LDA	
0221	85	7D		Sta	
0223	A9	E6		LDA	
0225	85	7E		STA	
0227	A9	70		LDA	define fuel-air ratio 70~1/14, 73~1/16, 76~1/18, 79~1/20
0229	8D	8C	02	STA	
022C	EA			NOP	
022D	A9	F8		LDA	initialize air flow rate for 2 lb/min
022F	85	81		STA	
0231	A9	1F		LDA	
0233	85	82		STA	
0235	A9	F4		LDA	
0237	85	83		STA	
0239	A9	85		LDA	specify $\overline{NMI}$ vector, low byte
023B	8D	FA	17	STA	
023E	A9	27		LDA	specify $\overline{NMI}$ vector, high byte
0240	8D	FB	17	STA	
0243	A9	80		LDA	turn off all Tri-States and Latches
0245	8D	00	17	STA	
0248	58			CLI	clear intrupt disable
0249	4C	C4	02	JMP	jump to store constants

CONSTANT STORAGE PROGRAM

Address	Op Code	Operads Byte 1	Operads Byte 2	Mnemonic	Comment
02C4	A9	98		LDA	
02C6	85	4D		STA	
02C8	A9	A8		LDA	
02CA	85	4E		STA	
02CC	A9	EB		LDA	
02CE	85	51		STA	
02D0	A9	51		LDA	
02D2	85	52		STA	
02D4	A9	99		LDA	
02D6	85	54		STA	
02D8	85	69		STA	
02DA	85	73		STA	
02DC	A9	58		LDA	
02DE	85	55		STA	
02E0	A9	F1		LDA	
02E2	85	56		STA	
02E4	A9	1F		LDA	
02E6	85	57		STA	
02E8	A9	F2		LDA	store exponent of the injectors calibration
02EA	85	65		STA	
02EC	85	62		STA	
02EE	85	6E		LDA	
02F0	85	59		STA	
02F2	A9	45		LDA	
02F4	85	58		STA	
02F6	A9	EC		LDA	
02F8	85	5A		STA	
02FA	A9	95		LDA	
02FC	85	5B		STA	
02FE	A9	F3		LDA	
0300	85	5C		STA	
0302	A9	E1		LDA	
0304	85	5D		STA	
0306	A9	5A		LDA	
0308	85	5E		STA	
030A	A9	88		LDA	store the injectors calibration equation
030C	85	60		STA	
030E	A9	42		LDA	
0310	85	61		STA	
0312	A9	7C		LDA	
0314	85	63		STA	
0316	A9	40		LDA	

CONSTANT STORAGE PROGRAM - Continued

0318	85	64	STA
031A	A9	A8	LDA
031C	85	66	STA
031E	A9	61	LDA
0320	85	67	STA
0322	A9	02	LDA
0324	85	68	STA
0326	A9	7D	LDA
0328	85	6A	STA
032A	A9	dF	LDA
032C	85	6C	STA
032E	A9	46	LDA
0330	85	6D	STA
0332	A9	25	LDA
0334	85	70	STA
0336	A9	r9	LDA
0338	85	71	STA
033A	A9	EE	LDA
033C	85	72	STA
033E	85	75	STA
0340	A9	40	LDA
0342	85	74	STA
0344	A9	C7	LDA
0346	85	78	STA
0348	A9	71	LDA
034A	85	77	STA
034C	A9	ED	CDA
034E	85	78	STA
0350	85	7B	STA
0352	A9	66	LDA
0354	85	79	STA
0356	85	7A	STA
0358	A9	F5	LDA
035A	85	4A	STA
035C	85	6B	STA
035E	A9	68	LDA
0360	85	4B	STA
0362	A9	Fø	LDA
0364	85	4C	STA
0366	85	4F	STA
0368	85	53	STA
036A	85	5F	STA
036C	A9	00	LDA
036E	85	47	STA
0370	85	92	STA
0372	85	98	STA
0374	85	A4	STA
0376	85	A7	STA

CONSTANT STORAGE PROGRAM - Continued

0378	85	39	STA
037A	85	3E	STA
037C	A9	20	LDA
037E	85	48	STA
0380	A9	F2	LDA
0382	85	49	STA
0384	85	A6	STA
0386	A9	89	LDA
0388	85	8F	STA
038A	A9	EB	LDA
038C	85	91	STA
038E	85	A3	STA
0390	A9	41	LDA
0392	85	90	STA
0394	A9	60	LDA
0396	85	93	STA
0398	A9	Fr	LDA
039A	85	94	STA
039C	A9	AE	LDA
039E	85	95	STA
03A0	A9	47	LDA
03A2	85	96	STA
03A4	A9	ED	LDA
03A6	85	97	STA
03A8	A9	42	LDA
03AA	85	99	STA
03AC	A9	F7	LDA
03AE	85	9A	STA
03B0	85	A9	STA
03B2	A9	BF	LDA
03B4	85	9B	STA
0386	A9	58	LDA
03B8	85	9C	STA
03BA	A9	EC	LDA
03BC	85	9D	STA
03BE	A9	AB	LDA
93C0	85	9E	STA
03C2	Ao	72	LDA
03C4	85	9F	STA
03C6	A9	F5	LDA
03C8	85	A0	STA
03CA	A9	E1	LDA
03CC	85	A1	STA
03CE	A9	7A	LDA
03D0	85	A2	STA
03D2	A9	40	LDA
03D4	85	A5	STA
03D6	A9	4C	LDA
03D8	85	A8	STA

CONSTANT STORAGE PROGRAM - Continued

03DA	A9	52		LDA	
03DC	85	3A		STA	
03DE	A9	F9		LDA	
03E0	85	3B		STA	
03E2	A9	61		LDA	
03E4	85	3C		STA	
03#6	A9	51		LDA	
03E8	85	3D		STA	
03EA	A9	00		LDA	load 5000, F_4 for spark advance delay
03EC	85	19		STA	
03EE	A9	50		LDA	
03F0	85	1A		STA	
03F2	A9	F4		LDA	
03F4	85	1B		STA	
03F6	EA			NOP	
03F7	EA			NOP	
03F8	EA			NOP	
03F9	EA			NOP	
03FA	EA			NOP	
03FB	EA			NOP	
03FC	4C	60	28	JMP	jump to initialize the data recording program
2860	A9	00		LDA	
2862	8D	05	29	STA	
2865	A9	30		LDA	
2867	8D	06	29	STA	
286A	A9	60		LDA	
286C	80	3A	29	STA	
286F	A9	32		LDA	
2871	8D	3B	29	STA	
2874	A9	BO		LDA	
2876	8D	D5	28	STA	
2879	A9	3C		LDA	
287B	8D	D6	28	STA	
287E	A9	20		LDA	
2880	8D	A4	29	STA	
2883	A9	37		LDA	
2885	8D	A5	29	STA	
2888	A9	80		LDA	
288A	8D	E3	28	STA	
288D	A9	39		LDA	
288F	8D	E4	28	STA	
2892	A9	EO		LDA	
289A	8D	OC	2A	STA	
2897	A9	3B		LDA	
2899	8D	OD	2A	STA	
289C	4C	50	02	JMP	jump to 0250 injection program

INJECTION PROGRAM

Address	Op Code	Operands Byte 1	Operands Byte 2	Mnemonic	Comment
0250	A2	02		LDX	adjust rpm
0252	B5	7C		LDA,X	
0254	95	01		STA,X	
0256	CA			DEX	
0257	10	F9		BPL	
0259	A2	02		LDX	
025B	B5	6C		LDA,X	
025D	95	04		STA,X	
025F	CA			DEX	
0260	10	F9		BPL	
0262	20	00	20	JSR	jump to multiply subroutine
0265	A2	02		LDX	
0267	B5	26		LDA,X	
0269	95	89		STA,X	
026B	CA			DEX	
026C	10	F9		BPL	
026E	EA	EA	EA	NOP	
0271	20	00	23	JSR	jump to air flow rate conversion
0274	A2	02		LDX	
0276	B5	86		LDA,X	set up registers to multiply 1/2N by air flow rate
0278	95	01		STA,X	
027A	CA			DEX	
027B	10	F9		BPL	
027D	A2	02		LDA	
027F	B5	89		LDA,X	
0281	95	04		STA,X	
0283	CA			DEX	
0284	10	F9		BPL	
0286	20	00	20	JSR	jump to multiply subroutine
0289	A2	02		LDX	
028B	B5	70		LDA,X	
028D	95	01		STA,X	set up registers to multiply fuel-air ratio by product of 1/2N and air flow rate
028F	CA			DEX	
0290	10	F9		BPL	
0292	A2	02		LDA	
0294	B5	26		LDA,X	
0296	95	04		STA,X	
0298	CA			DEX	
0299	10	F9		BPL	
029B	20	00	20	JSR	

INJECTION PROGRAM - Continued

029E	A2	02		LDX	set up registers to scale mass of fuel per injection by 10^5
02A0	B5	26		LDA,X	
02A2	95	01		STA,X	
02A4	CA			DEX	
02A5	10	F9		BPL	
02A7	A2	02		LDX	
02A9	B5	66		LDA,X	
02AB	95	04		STA,X	
02AD	CA			DEX	
02AE	10	F9		BPL	
02B0	20	00	20	JSR	jump to multiply subroutine
02B3	A2	02		LDX	
02B5	B6	26		LDA,X	
02B7	95	B0		STA,X	
02B9	CA			DEX	
02BA	10	F9		BPL	
02BC	20	00	24	JSR	jump to compute injection pulse
02BF	4C	D0	24	JMP	jump to rpm conversion subroutine
02C2	EA			NOP	
02C3	EA			NOP	

AIR FLOW SENSOR CALIBRATION PROGRAM

2300	D8			CLD	
2301	38			SEC	
2302	A5	81		LDA	compare count of air flow sensor voltage with 1FF8
2304	E9	F8		SBC#	
2306	A5	82		LDA	
2308	E9	1F		SBC#	
230A	10	1F		BPL	branch to 232C if CAFSV 1FF8
230C	EA			NOP	
230D	EA			NOP	
230D	EA			NOP	
230E	EA			NOP	
230F	AZ	02		LDX	
2311	B5	81		LDA,X	
2312	95	01		STA,X	
2315	CA			DEX	
2316	10	F9		BPL	branch to 2311 if x-reg is positive
2318	A2	02		CDX	
231A	B5	SD		LDA,X	
231C	95	04		STA,X	
231E	CA			DEX	
231F	10	F9		BPL	
2321	20	00	20	JSR	jump to multiply subroutine
2324	EA			NOP	

AIR FLOW SENSOR CALIBRATION PROGRAM - Continued

2325	EA			NOP	
2326	EA			NOP	
2327	EA			NOP	
2328	EA			NOP	
2329	4C	E4	23	JMP	jump to 23E4, store the final result
232C	D8			CLD	
232D	38			SEC	
232F	A5	81		LDA	compre count of air flow sensor voltage with 3FF0
2331	E9	F0		SBC	
2333	A5	82		LDA	
2335	E9	3F		SBC	
2337	10	39		BPL	branch to 2370 if CAFSV 3FF0
2339	EA			NOP	
233A	EA			NOP	
233B	EA			NOP	
233C	EA			NOP	
233B	A2	02		LDX	
233D	B5	81		LDA,X	
233F	95	30		STA,X	
2341	CA			DEX	
2342	10	F9		BPL	branch to 233D if X-Reg is positive
2344	A2	02		LDX	
2346	B5	4D		LDA,X	
2348	95	33		STA,X	
234A	CA			DEX	
234B	10	F9		BPL	branch to 2346 if X-reg is positive
234D	20	40	21	JSR	jump to addition subroutine
2350	EA			NOP	
2351	EA			NOP	
2352	EA			NOP	
2353	EA			NOP	
2354	A2	02		LDX	
2356	B5	36		LDA,X	
2358	95	01		STA,X	
235A	CA	EA		DEX	
235C	10	F8		BPL	branch to 2356 if x-reg is positive
235E	A2	02		LDX	
2360	B5	4A		LDA,X	
2362	95	04		STA,X	
2364	CA			DEX	
2365	10	F9		BPL	branch to 2360 if x-reg is positive
2367	20	00	20	JSR	jump to multiply subroutine
236A	EA			NOP	
236B	EA			NOP	
236C	EA			NOP	
236D	4C	E4	23	JMP	jump to 23E4, store the final result

AIR FLOW SENSOR CALIBRATION PROGRAM - Continued

2370	D8			CLD	
2371	38			SEC	
2372	A5	81		LDA	compare count of air flow sensor voltage with 4FF1
2374	E9	F1		SBC	
2376	A5	82		LDA	
2378	E9	4F		SBC	
237A	10	35		BPL	branch to 23B1 if CAFSV 4FF1
237C	A2	02		LDX	
237E	B5	81		LDA,X	
2380	95	30		STA,X	
2382	CA			DEX	
2383	10	F9		BPL	branch to 237E if x-ray is positive
2385	A2	02		LDX	
2387	B5	54		LDA,X	
2389	95	33		STA,X	
238B	CA			DEX	
238C	10	F9		BPL	branch to 2387 if x-reg is positive
238E	20	40	21	JSR	
2391	EA			NOP	
2392	EA			NOP	
2393	EA			NOP	
2394	EA			NOP	
2395	EA			NOP	
2396	A2	02		CDX	
2398	B5	36		CDA,X	
239A	95	01		STA,X	
239C	CA			DEX	
239D	10	F9		BPL	branch to 2396 if x-reg is positive
239F	A2	02		LDX	
23A1	B5	51		LDA,X	
23A3	95	04		STA,X	
23A5	CA			DEX	
23A6	10	F9		BPL	branch to 23A1 if x-reg is positive
23A8	20	00	20	JSR	jump to multiply subroutine
23AB	EA			NOP	
23AC	EA			NOP	
23AD	EA			NOP	
23AE	4C	E4	23	JMP	jump to store final result
23B1	A2	02		LDX	
23Bc	B5	81		LDA,X	
23B5	95	30		STA,X	
23B7	CA			DEX	
23B8	10	F9		BPL	branch to 23B3 if x-reg is positive
23BA	A2	02		LDX	
23BC	B5	5A		LDA,X	
23BE	95	33		STA,X	
23C0	CA			DEX	
23C1	10	F9		BPL	branch to 23BC if x-reg is positive

AIR FLOW SENSOR CALIBRATION PROGRAM - Continued

```
23C3    20    40    21    JSR     jump to addition subroutine
23C6    EA                NOP
23C6    EA                NOP
23C8    EA                NOP
23C9    EA                NOP
23CA    EA                NOP
23CB    A2    92          LDX
23CD    B5    36          LDA,X
23CF    95    01          STA,X
23D1    CA                DEX
23D2    10    F9          DPL     branch to 23CD if x-reg is positive
23D4    A2    02          LDX
23D6    B5    57          LDA,X
23D8    95    04          STA,X
23DA    CA                DEX
23DB    10    F9          BPL     branch to 23D6 if x-reg is positive
23DD    20    00    20    JSR     jump to multiply subroutine
23E0    EA                NOP
23E1    EA                NOP
23E2    EA                NOP
23E3    EA                NOP
23E4    A2    02          LDX#
23E6    Bt    26          LDA,X
23E8    95    86          STA,X
23EA    CA                DEX
23EB    10    F9          BPL     branch to 23E6 if x-reg is positive
23ED    60
```

FUEL INJECTORS CALIBRATION PROGRAM

```
2400    D8                CLD
2401    18                CLC
2402    EA                NOP
2403    EA                NOP
2404    EA                NOP
2405    EA                NOP
2406    EA                NOP
2407    A2    02          LDX     store the value of mass of fuel
                                     per injection into the addition
                                     register
2409    B5    B0          LDA,X
240B    95    30          STA,X
240D    CA                DEX
240E    10    F9          BPL     branch to 2409 if x-reg is positive
2410    A2    02          LDX
2412    Bt    63          LDA,X   store value of 1.0076 into the
                                     addition register
```

FUEL INJECTORS CALIBRATION PROGRAM - Continued

2414	95	33		STA,X	
2416	CA			DEX	
2417	10	F9		BPL	branch to 2414 if x-reg is positive
2419	20	40	21	JSR	jump to addition subroutine
241C	EA			NOP	
241D	EA			NOP	
241E	EA			NOP	
241F	EA			NOP	
2420	A2	02		LDX	store result of the previous addition into the multiplication register
2422	B5	36		LDA,X	
2424	95	01		STA,X	
2426	CA			DEX	
2427	10	F9		BPL	branch to 2422 if x-reg is positive
2429	A2	02		LDX	
242B	B5	60		LDA,X	store value of 1.0396 into the multiplication register
242D	95	04		STA,X	
242F	CA			DEX	
2430	10	F9		BPL	branch to 242B if x-ray is positive
2432	20	00	20	JSR	
2435	A2	02		LDX	store the result injection pulse into the proper register
2437	B5	26		LDA,X	
2439	95	B3		STA,X	
243B	CA			DEX	
243C	10	F9		BPL	branch to 2437 if x-reg is positive
243E	EA			NOP	
243F	EA			NOP	
2440	EA			NOP	
2441	EA			NOP	
2442	A2	02		LDX	adjust the value of injection pulse for 8-bit value
2444	B5	B3		LDA,X	
2446	95	01		STA,X	
2448	CA			DEX	
2449	10	F9		BPL	branch to 2444 if x-ray is positive
244B	A2	02		LDX#	
244D	B5	69		LDA,X	
244F	95	04		STA,X	
2451	CA			DEX	
2452	EA			NOP	
2453	10	F8		BPL	branch to 244D if x-reg is positive
2455	20	00	20	JSR	jump to multiply subroutine to adjust injection pulse
2458	EA			NOP	
2459	EA			NOP	
245A	EA			NOP	
245B	A5	29		CDA	

FUEL INJECTORS CALIBRATION PROGRAM - Continued

245D	10	0F		BPL	branch to 246E if exp. of injection pulse is positive
245F	46	27		LSR	
2461	66	26		ROR	adjust injection pulse for zero exp.
2463	66	25		ROR	
2465	66	24		ROR	
2467	E6	29		INC	
2469	30	F4		BMI	branch to 245F if exp. of IP is negative
246B	4C	7D	24	JMP	
246E	F0	0F		BEQ	branch to 247F if exp. of IP is zero
2470	06	24		ASL	
2472	26	25		ROL	adjust injection pulse for zero exp.
2474	26	26		ROL	
2476	26	27		ROL	
2478	C6	29		DEC	
247A	Dø	F4		BNE	
247C	EA			NOP	
247D	EA			NOP	
247F	A5	24		LDA	store final result of injection pulse in the proper register
248I	85	EE		STA	
2483	60			RTS	return from the subroutine

SPEED (RPM) CALCULATION PROGRAM

24D0	A2	02		CDX	load value of 1/2N into divisor register of divide subroutine
	B5	89		CDA,X	
	95	0D		STA,X	
	CA			DEX	
	10	F9		BPL	
	A2	02		CDX	
	B5	47		CDA,X	load value of 0.5 decimal into dividend of divide subroutine
	95	0A		STA,X	
	CA			DEX	
	10	F9		BPL	
	EA			NOP	
	EA			NOP	
	EA			NOP	
	20	00	25	JSR	jump to divide subroutine
	A2	02		CDX	
	B5	10		CDA,X	store result of speed (rpm) into the proper registers
	95	8C		STA,X	
	CA			DEX	

SPEED (RPM) CALCULATION PROGRAM - Continued

```
        10    F9          BPL
        4C    D0    25    JMP     jump to spark advance program
```

SPARK ADVANCE SUBROUTINE

```
25D9    A2    02          LDX     adjust speed (rpm) for constant
                                    exp. of -3
25D2    B5    8C          LDA,X
25D4    95    2C          STA,X
25D6    CA                DEX
25D7    10    F9          BPL
25D9    A9    FD          LDA-#
25DB    C5    2E          CMP
25DD    F0    09          BEQ     branch to 25E8 if exp. of rpm is -3
25DF    46    2D          LSR
25E1    66    2C          ROR
25E3    E6    2E          INC
25E5    4C    D9    25    JMP     jump to 25D9 to test exp of rpm
25E8    D8                CCD
25E9    38                SEC     compare rpm with 750 Dec or 1770,
                                     FD Hex
25EA    AS    2C          LDA-ze
25EC    E9    70          SBC-ze
25EE    A5    2D          LDA-ze
25F0    E9    17          SBC-ze
25F2    10    0B          BPL     branch to 25FF if rpm 1750
25F4    A9    00          LDA#
25F6    85    AD          STA-ze set spark advance equal to zero
                                     if rpm 750
25F8    85    AE          STA-ze
25FA    85    AF          STA-ze
25FC    4C    B9    26    JMP     jump to the end of program
25FF    EA                NOP
2600    EA                NOP
2601    EA                NOP
2602    38                SEC-ze
2603    A5    2C          LDA-ze compare rpm with 1000 Dec or
                                     1F40,FD Hex
2605    E9    40          SBC-ze
2607    A5    2D          LDA-ze
2609    E9    1F          SBC-ze
260B    10    1C          BPL     branch to 2629 if rpm 1000
260D    A2    02          LDX
260F    B5    8F          LDA,X
2611    EA                NOP
2612    95    01          STA,X
```

SPARK ADVANCE SUBROUTINE - Continued

2614	CA			DEX	
2615	10	F8		BPL	
2617	20	BF	26	JSR	jump to intermediate subroutine
261A	A2	02		LDX	
261C	B5	92		LDA,X	load hex value of 6.0 into the subtraction register
261E	95	33		STA,X	
2620	CA			DEX	
2621	10	F9		BPL	
2623	20	Bø	26	JSR	jump to subtraction surroutine
2626	4C	BO	26	JMP	jump to the end of program
2629	EA			NOP	
262A	EA			NOP	
262B	EA			NOP	
262C	38			SEC	
262D	A5	2C		LDA-ze	compare rpm with 1400 dec. or 2BC(o FD hex
262F	E9	CO		SBC-#	
2631	A5	2D		LDA-ze	
2633	E9	2B		SBC-#	
2635	10	1B		BPL	branch to 2652 if rpm 1400 dec
2637	A2	02		LDX	
2639	B5	95		LDA,X	load hex value of .035 into the multiplication register
263B	95	01		STA,X	
263D	CA			DEX	
263E	10	F9		BPL	
2640	20	BF	26	JSR	jump to intermidiate subroutine
2643	A2	02		LDX	
2645	B5	98		LDA,X	load hex value of 33.0 into the subtraction register
2647	95	33		STA,X	
2649	CA			DEX	
264A	10	F9		BPL	
264C	20	BO	25	JSR	jump to the subtraction subroutine
264F	4C	BO	26	JMP	jump to the end of program
2652	EA			NOP	
2653	EA			NOP	
2654	EA			NOP	
2655	38			SEC	
2656	A5	2C		LDA-ze	compare rpm with 2000 dec. or 3E80, FD hex
2658	#9	80		SBC-#	
265A	A5	2D		LDA-ze	
265C	E9	3E		SBC-#	
265E	10	1B		BPL	branch to 267B if rpm 2000
2660	A2	02		LDX	
2662	B5	9B		LDA,X	load value of .02167 into the multiplication register

SPARK ADVANCE SUBROUTINE - Continued

```
2664    95      01              STA,X
2666    CA                      DEX
2667    10      F9              BPL
2669    20      BF      26      JSR     jump to subtraction subroutine
266C    A2      02              LDX
266E    B5      9E              LDA,X   load hex value of 14.333 into the
                                            subtraction register
2670    95      33              STA,X
2672    CA                      DEX
2673    10      F9              BPL
2675    20      B0      26      JSR     jump to subtraction subroutine
2678    4C      B0      26      JMP     jump to the end of program
267B    38                      SEC
267C    A5      2C              LDA-ze compare rpm with 2600 dec. or 5140,
                                            FD hex.
267E    E9      40              SBC#
2680    A5      2D              LDA#
2682    E9      51              SBC#
2684    10      1B              BPL     branch to 26A1 if rpm  2600
2686    A2      02              LDX
2688    B5      A1              LDA,X   load hex, value of .015 into the
                                            multiplication subroutine
268A    95      01              STA,X
268C    CA                      DEX
268D    10      F9              BPL
268F    20      BF      26      JSR     jump to intermidiate subroutine
2692    A2      02              LDX
2694    B5      A4              LDA,X   load hex value of 1.0 into the
                                            subtraction register
2696    95      33              STA,X
2698    CA                      DEX
2699    10      F9              BPL
269B    20      B0      25      JSR     jump to subtraction subroutine
269E    4C      B0      26      JMP     jump to the end of program
26A1    EA                      NOP
26A2    EA                      NOP
26A3    EA                      NOP
26A4    A2      02              LDX
26A6    B5      A7              LDA,X   load 38 deg. in dec. of 4C00, F7
                                          in hex. for spark advance when
                                          rpm  2600
26AA    CA                      DEX
        26AB    10      F9              BPL
26AD    4C      00      27      JMP     jump to ignition program
26B0    A2      02              LDX
26B2    B5      36              LDA,X   store final computed value of
                                            spark advance in the proper
                                            memory location
26B4    95      AD              STA,X
```

SPARK ADVANCE SUBROUTINE -Continued

26B6	CA			DEX	
26B7	10	F9		BPL	
26B9	4C	00	27	JMP	jump to ignition program
26BC	EA			NOP	
26BD	EA			NOP	
26BE	EA			NOP	
26BF	A2	02		LDX	load exact value of speed (rpm) into the multiplication subroutine
26C1	B5	8C		LDA,X	
26C3	95	04		STA,X	
26C5	CA			DEX	
26C6	10	F9		BPL	
26C8	20	00	20	JSR	jump to multiplication subroutine
26CB	A2	02		LDX	
26CD	B5	26		LDA,X	load result of multiply into the addition register
26CF	95	30		STA,X	
26C1	CA			DEX	
26D2	10	F9		BPL	
26D4	60			JSR	jump from subroutine

IGNITION PROGRAM

2700	A2	02		LDX	load value of (180-ϕ deg into the addition register
2702	B5	39		LDA,X	
2704	95	30		STA,X	
2706	CA			DEX	
2707	10	F9		BPL	
2709	A2	02		LDX	load value of spark advance into the subtraction register
270B	B5	AD		LDA,X	
270D	95	33		STA,X	
270F	CA			DEX	
2710	10	F9		BPL	
2712	20	B0	25	JSR	jump to subtraction subroutine
2715	A2	02		LDX	
2717	B5	36		LDA,X	load result of subtraction into the multiply register
2719	95	01		STA,X	
271B	CA			DEX	
271C	10	F9		BPL	
271E	A2	02		LDX	
2720	B5	89		LDA,X	load value of 1/2 (rpm) into the multiply register

IGNITION PROGRAM - Continued

```
2722    95    04          STA,X
2724    CA                DEX
2725    10    F9          BPL
2727    20    00    20    JSR    jump to multiplication subroutine
272A    A2    02          LDX
272C    B5    26          LDA,X  load result of multiply into the
                                    multiply subroutine
272E    95    01          STA,X
2730    CA                DEX
2731    10    F9          BPL
2733    A2    02          LDX    load hex value of 10^6/48 into the
                                    multiply subroutine
2735    B5    3C          LDA,X
2737    95    04          STA,X
2739    CA                DEX
273A    10    F9          BPL
273C    20    00    20    JSR    Jump to multiplication subroutine
273F    A2    02          LDX
2741    B5    26          LDA,X  load result of multiply into the
                                    addition register
2743    95    30          STA,X
2745    CA                DEX
2746    10    F9          BPL
2748    A2    02          LDX    load value of 80 us for interupt
                                    delay into the subtraction
                                    register
274A    B5    19          LDA,X
274C    95    33          STA,X
274E    CA                DEX
274F    10    F9          BPL
2751    20    BO    25    JSR    jump to subtraction subroutine
2754    A2    02          LDX
2756    B5    36          LDA,X  store result of ignition time in
                                    the proper registers
2758    95    1D          STA,X
275A    CA                DEX
275B    10    F9          BPL
275D    A9    FD          LDX    test ignition time for exp. of -3
275F    C5    1F          CMP
2761    Fø    09          BEQ    branch to 276C if exp is -3
2763    46    1E          LSR-ze adjust exp of ignition time for -3
2765    66    1D          ROR-ze
2767    E6    1F          INC
2769    4C    5D    27    JMP    jump to 275D to test exp
276C    A5    1D          CDA-ze
276E    85    84          STA-ze adjust ignition time for 12-bit
                                    ignition counters, store final
                                    adjusted value in memory
                                    location 0084 and 0085
```

IGNITION PROGRAM - Continued

```
2770    A5    1E          LDA-ze
2772    85    85          STA-ze
2774    46    85          LSR-ze
2776    66    85          ROR-ze
2778    46    84          LSR-ze
277A    46    84          LSR-ze
277C    4C    90    24    JMP     jump to display su broutine
277F    EA                NOP
```

NON-MASKABLE INTERRUPT

```
2785    48                PHA     save accumulator
2786    AD    00    17    LDA     test injection pulse
2789    4A                LSRA
278A    B0    46          BCS     branch to 27D2 if injection pulse
                                     is high
278C    A5    EE          LDA-ze set injection pulse count
278E    8D    0E    17    STA-ze
2791    A9    01          LDA#    turn on injection pulse
2793    0D    00    17    ORA-Ab
2796    8D    00    17    STA-Ab test distributor signal
2799    30    35          BMI     branch to 27D0 if it is high
279B    A9    01          LDA-#   waite 80 micrsecond
279D    85    46          STA-ze
279F    C6    46          DEC
27A1    D0    FC          BNE
27A3    A9    3F          LDA#    set direction of the B-register
                                     as output
27A5    8D    03    17    STA-Abs
27A8    A5    85          LDA-ze load high byte of ignition time
                                     into the B-register
27AA    8D    02    17    STA-Abs
27AD    A9    21          LDA-#
27AF    8D    00    17    STA-Abs turn off latch No. 2
27B2    A9    01          LDA-#
27B4    8D    00    17    STA-Abs turn off latch No. 2
27B7    A5    84          CDA-ze
27B9    8D    02    17    STA-Abs
27BC    A9    41          CDA#
27BE    8D    00    17    STA-Abs turn on latch No. 1
27C1    A9    61          LDA#
27C3    8D    00    17    STA-Abs turn off latch No. 1 and turn on
                             parallel load
27C6    A9    00          LDA-#
27C8    8D    03    17    STA-Abs set direction of the B-register
                              as input
```

NON-MASKABLE INTERRUPT - Continued

```
27CB     A9     01            LDA-#
27CD     8D     00     17     STA-Abs turn off parallel load
27D0     68                   PLA     resore accumulator
27D1     40                   RTI     return from interrupt program
27D2     4C     45     28     JMP     jump to 2845 to save x-register
27D5     EA                   NOP
27D6     EA                   NOP
27D7     A9     80            LDA-#   turn off injection pulse
27D9     2D     00     17     AND-Abs
27DC     8D     00     17     STA-Abs
27DF     10     25            BPL     test distributor signal and
                                        branch to 2806 if it is low
27E1     A9     02            CDA-#
27E3     8D     00     17     STA-Abs turn on high byte of air-flow
                                        count tri-state
27E6     AD     02     17     LDA-Abs read high byte of air-flow count
                                         and adjust
27E9     29     3F            AND
27EB     85     82            STA-ze
27ED     A9     00            CDA-#
27EF     8D     00     17     STA-Abs turn off high byte of air-flow
                                         count Tri-state
27F2     A9     04            LDA-#
27F4     8D     00     17     STA-Abs turn on low byte of air-flow
                                         count Tri-State
27F7     AD     02     17     LDA-Abs read low byte of air-flow count
                                         and adjust
27FA     29     FC            AND
27FC     0A                   ASL
27FD     0A                   ASL
27FE     0A                   ASL
27FF     85     81            STA
2801     26     82            ROL
2803     4C     35     28     JMP     jump to the end of interrupt
                                         program
2806     EA                   NOP
2807     A9     28            LDA-#   turn on high byte of rpm count
                                        latch and tri-states
2809     8D     00     17     STA-Abs
280C     A9     08            LDA-#
280E     8D     00     17     STA-ABS turn off high byte of rpm count
                                         latches
2811     AD     02     17     LDA-Abs read high byte of rpm count and
                                         adjust
2814     29     3F            AND-#
2816     85     7D            STA-ze
2818     A9     00            LDA-#   turn off tri states of high byte
                                        rpm count
```

NON-MASKABLE INTERRUPT -Continued

281A	8D	00	17	STA-Abs	
281D	A9	50		LDA-#	turn on tri states and latches of low byte of rpm
281F	8D	00	17	STA-Abs	
2822	A9	10		LDA-#	
2824	8D	00	17	STA-Abs	turn off latches of low byte of rpm count
2827	AD	02	17	LDA-Abs	read low byte of rpm count and adjust
282A	OA			ASL-A	
282B	OA			ASL-A	
282C	OA			ASL-A	
282D	85	7C		STA	
282F	26	7D		ROL	
2831	A9	E7		LDA-#	
2833	85	7E		STA-ze	
2835	A9	00		LDA-#	
2837	8D	00	17	STA-Abs	
283A	4C	00	29	JMP	jump to data testing program reload x-register
283D	68			PLA	
283E	AA			TAX	
283F	68			PLA	reload accumulator from stack
2840	40			RTI	
2841	EA			NOP	
2842	EA			NOP	
2843	EA			NOP	
2844	EA			NOP	
2845	EA			NOP	
2846	EA			NOP	
2847	EA			NOP	
2848	8A			TXA	save x-register
2849	48			PHA	
284A	A9	FF		LDA	
284C	8D	OF	17	STA	
284F	4C	D5	27	JMP	
2852	EA			NOP	

MULTIPLICATION SUBROUTINE

2000	EA	EA	EA	NOP	
2003	EA	EA		NOP	
2005	A5	01		LDA	enter the multiplicand into the proper register
2007	85	20		STA	
2009	A5	02		LDA	
200B	85	21		STA	

MULTIPLICATION SUBROUTINE -Continued

200D	A5	04	LDA	enter the multiplier into the proper register
200F	85	22	STA	
2011	A5	05	LDA	
2013	85	23	STA	
2015	D8		CLD	specify the binary made clear all intermidiate registers
2016	A9	00	LDA-#	
2018	85	24	STA	
201A	85	25	STA	
201C	85	26	STA	
201E	85	27	STA	
2020	85	28	STA	
2022	85	29	STA	
2024	85	2A	STA	
2026	85	2B	STA	
2028	85	07	STA	
202A	EA		NOP	
202B	EA		NOP	
202C	EA		NOP	
202D	EA		NOP	
202E	EA		NOP	
202F	A2	10	LDX	load x-register with decimal 16
2031	A5	21	CDA	test multiplicand high byte branch to 204D if it is zero branch to 2051 if it is positive
2033	F0	18	BEQ	
2035	10	1B	BPL	
2037	85	21	STA	
2039	38		SEC	
203A	A9	00	CDA-#	take care of the sign if multiplicand megative
203C	E5	20	SBC	
203E	85	20	STA	
2040	A9	00	LDA-#	
2042	E5	21	SBC	
2044	85	21	STA	
2046	A5	07	CDA	
2048	18		CLC	
2049	69	80	ADC-#	turn on the flag no. 1
204B	85	07	STA	
204D	A5	20	LDA	test multiplicand low byte branch bo 20B7 if it is zero
204F	F0	66	BEQ	
2051	EA		NOP	
2052	EA		NOP	
2053	EA		NOP	
2054	A5	23	LDA	test multiplier high byte branch to 2073 if it is zero

MULTIPLICATION SUBROUTINE - Continued

				branch to 2077 if it is positive
2056	F0	1B	BEQ	
2058	10	1D	BPL	
205A	85	23	STA	
205C	38		SEC	
205D	A9	00	LDA-#	take care of the sign if-multi-
				plier is negative
205F	ES	22	SBC	
2061	85	22	STA	
2063	A9	00	LDA-#	
2065	ES	23	SBC	
2067	85	23	STA	
2069	A5	07	LDA	
206B	18		CLC	
206C	69	80	ADC-#	turn off the flay No. 1
206E	85	07	STA	
2070	EA		NOP	
2071	EA		NOP	
2072	EA		NOP	
2073	AS	22	CDA	test multiplier low byte branch
				to 20B7 if it is zero
2075	F0	40	BEQ	
2077	EA		NOP	
2078	AS	20	LDA	transfer multiplicand into the new
207A	85	28	STA	register
207C	AS	21	CDA	
207E	85	29	STA	
2080	18		CLC	
2081	46	23	LSR	shift multiplier right and test
				lowest bit
2083	66	22	ROR	
2085	90	1D	BCC	branch to 20A4 if it is zero
2087	18		CLC	
2088	EA		NOP	
2089	EA		NOP	
208A	EA		NOP	
208B	EA		NOP	
208C	A5	28	CDA	
208E	65	24	ADC	add content of intermidiate-
				register to content of the
				result register
2090	85	24	STA	
2092	A5	29	LDA	
2094	65	25	ADC	
2096	85	25	STA	
2098	A5	2A	LDA	
209A	65	26	ADC	
209C	85	26	STA	

MULTIPLICATION SUBROUTINE - Continued

209E	A5	2B		LDA	
20A0	65	27		ADC	
20A2	85	27		STA	
20A4	18			CLC	
20A5	06	28		ASL	shift intermidiate register to left
20A7	26	29		ROL	
20A9	26	2A		ROL	
20AB	26	2B		ROL	
20AD	CA			DEX	decrement x-register
					branch to 20B2 if x-register is zero
					branch to 2080 if x-register is not zero
20AE	F0	02		BEQ	
20B0	D0	CE		BNE	
20B2	EA			NOP	
20Be	EA			NOP	
20B4	4C	BA	20	JMP	jump to 20BA
20B7	4C	28	21	JMP	jump to 2128 to set regult zero
20BA	D8			CLD	
20BB	18			CLC	
20BC	AS	03		CDA	add exponent of multiplier and multiplicant
20BE	65	06		ADC	
20C0	85	08		STA	
20C2	AA			TAX	transfer the exponent of the result to x-register
20C3	18			CLC	
20C4	A9	00		LDA-#	clear the flag no. 2
20C6	85	09		STA	
20C8	AS	27		CDA	test the highest bit of the result branch to 20D1 if it is zero
20CA	0A			ASLA	
20CB	90	04		BCC	
20CD	A9	80		CDA	turn on the flag no. 2
20CF	85	09		STA	
20D1	EA			NOP	
20D2	A5	27		CDA	
20D4	0A	0A		ASLA	
20D6	EA			NOP	
20D7	B0	0F		BCS	branch to 20E8 if the previous test is 1
20D9	06	24		ASL	shift the result in order to adjust its one to highest bit 1
20DB	26	25		ROL	
20DD	26	26		ROL	
20DE	26	27		ROL	
20E1	CA			DEX	decrement exponent of the result
20E2	A5	27		LDA	

MULTIPLICATION SUBROUTINE - Continued

20E4	0A	0A	ASLA	test one to the highest bit of result branch to 20D9 if it is zero
20E6	90	F1	BCC	
20E8	A5	09	LDA	
20EA	0A		ASLA	test flay no. 2
20EB	90	04	BCC	branch to 20F1 if it is zero
20ED	A9	80	LDA	
20EF	05	27	ORA	
20F1	86	29	STX	
20F3	EA	EA	NOP	
20F5	EA	EA	NOP	
20F7	A5	07	LDA	test flag no. 1 branch to 2114 if it is off
20F9	10	19	BPL	
20FB	38		SEC	
20FC	A9	00	LDA-#	change the result to negative
20FE	E5	24	SBC	
2100	85	24	STA	
2102	A9	00	LDA	
2104	ES	25	SBC	
2106	85	25	STA	
2108	A9	00	LDA-#	
210A	E5	26	SBC	
210C	85	26	STA	
210E	A9	00	LDA-#	
2110	E5	27	SBC	
2112	85	27	STA	
2114	EA	EA	NOP	
2116	D8		CLD	
2117	18		CLC	
2118	A9	10	LDA-#	adjust exponent if decimal point is is in front of 16th bit
211A	65	29	ADC	
211C	85	28	STA	
211E	18		CLC	
211F	A9	1C	LDA-#	adjust exponent if decimal point is in fron of 28th bit
2121	65	29	ADC	
2123	85	2A	STA	
2125	60		RTS	return from the subroutine
2126	EA	EA	NOP	
2128	A9	00	CDA-#	
212A	85	24	STA	set result equal to zero if one of the multiplier or multiplican is zero
212C	85	25		
212E	85	26		

MULTIPLICATION SUBROUTINE - Continued

2130	85	27		STA	
2132	85	28		STA	
2134	85	29		STA	
2136	85	2A		STA	
2138	85	2B		STA	
213A	60			RTS	return from the subroutine
213B	EA	EA		NOP	
213D	EA	EA		NOP	
213F	EA			NOP	

DIVIDE SUBROUTINE

2500	EA			NOP	
2501	EA			NOP	
2502	EA			NOP	
2503	EA			NOP	
2504	EA			NOP	
2505	EA			NOP	
2506	4C	85	25	JMP	jump to 2585 to adjust dividend
2509	A9	00		LDA-#	set partial quotient to zero
250B	85	10		STA-ze	
250D	85	11		STA-ze	
250F	85	12		STA-ze	
2511	A9	0E		LDY	load y-reg with deciman 14
2513	38			SEC	
2514	A5	13		LDA-ze	subtract divisor from divident
2516	E5	16		SBC-ze	
2518	85	13		STA-ze	
251A	A5	14		LDA-ze	
251C	E5	17		SBC-ze	
251E	85	14		STA-ze	
2520	30	16		BMI	branch to 2538 if result of above subtraction is negative
2522	A9	01		LDA-#	
2524	05	10		ORA-ze	
2526	85	10		STA-ze	set one on the LSB of quotient
2528	18			CLC	
2529	06	10		ASL-ze	shift quotient to left
252B	26	11		ROL-ze	
252D	18			CLC	
252E	06	13		ASL-ze	shift dividend to left
2530	26	14		ROL-ze	
2532	88			DEY	
2533	D0	DE		BNE	branch to 2513 if 6-reg is not zero
2535	4C	5B	25	JMP	jump to 255B
2538	18				

DIVIDE SUBROUTINE - Continued

2539	06	10		ASL-ze	shift quotient to left
243B	26	11		ROL-ze	
253D	18			CLC	
253E	06	13		ASL-ze	shift divident to left
2540	26	14		ROL-ze	
2542	D8			CLD	
2543	18			CLC	
2544	A5	13		LDA-ze	add dividend to divisor
2546	65	16		ADC-ze	
2548	85	13		STA-ze	
254A	A5	14		LDA-ze	
254C	65	17		ADC-ze	
254E	85	14		STA-ze	
2550	10	06		BPL	branch to 2558 if result of above addition is positive
2552	D0	E3		BNE	branch to 2539 if y-reg is not zero
2555	4C	5B	26	JMP	jump to 255B
2558	88			DEY	
2559	D0	C7		BNE	branch to 2522 if y-reg is not zero
255B	EA	EA		NOP	
255D	38			SEC	
255E	A5	15		LDA-ze	subtract exp. of divisor from exp. of divident
2560	E5	18		SBC-ze	
2562	85	12		STA-ze	store exp. of result
2564	18			CLC	
2565	A9	F2		LDA-#	add decimal-14 to exp. of result to adjust decimal point
2567	65	12		ADC-ze	
2569	85	12		STA-ze	
256B	A5	11		LDA-ze	test high byte of quotient
256D	D0	04		BND	branch to 2473 if not zero
256F	A5	10		LDA-ze	test low byte of quotient
2571	F0	0F		BEQ	branch to 2582 if it is zero
2573	A5	11		LDA-ze	
2575	0A			ASLA	
2576	0A			ASLA	
2577	B0	09		BCS	branch to 2582 if bit 14 of quotient is 1
2579	06	10		ASL	adjust bit 14 of quotient for 1
257B	26	11		ROL	
257D	C6	12		DEC	
257F	4C	73	25	JMP	
2582	60			RTS	
2583	EA			NOP	
2584	EA			NOP	
2585	38			SEC	adjust dividend so that to be less than divisor

DIVIDE SUBROUTINE - Continued

2586	A5	9A		LDA-ze	
2588	E5	0D		SBC-z3	
258A	A5	0B		LDA-ze	
258C	E5	0E		SBC-ze	
258E	30	09		BMI	
2590	46	0B		LSR-ze	
2592	66	0A		ROR-ze	
2594	E6	9C		INC-ze	
2596	4C	85	25	JMP	jump to 2585 to compare dividend and divisor
2599	A2	05		LDX	
259B	B5	0A		LDA,X	load value of divisor and dividend into the intermidiate registers
259F	CA			DEX	
25A9	10	F9		DPL	
25A2	4C	09	25	JMP	

ADDITION SUBROUTINE

2140	A5	30		CDA	test first number if it is zero
2142	Dφ	07		BNE	
2144	A5	31		CDA	
2146	Dφ	03		BNE	
2148	4C	41	22	JMP	jump to test other number for zero
214B	4C	26	22	JMP	jump to set result equal to the first number
214E	EA	EA		NOP	
2150	A5	30		LDA	enter two numbers need to added into the intermidiate register
2152	85	40		STA	
2154	A5	31		LDA	
2156	85	41		STA	
2158	A5	32		CDA	
215A	85	42		STA	
215C	A5	33		CDA	
215E	85	43		STA	
2160	A5	34		CDA	
2162	85	44		STA	
2164	A5	35		LDA	
2166	85	45		STA	
2168	A5	41		CDA	test first number for positive
216A	0A			ASLA	
216B	90	1B		BCC	branch to 2188 if it is positive
216D	A5	41		CDA	
216F	0A	0A		ASLA	test next to highest bit of the first number
2171	90	09		BCC	branch to 217C if it is zero

ADDITION SUBROUTINE - Continued

2173	06	40		ASL	
2175	26	41		ROL	adjust first number to have its one to highest bit o for negative nubmer
2177	C6	42		DEC	
2179	EA	EA		NOP	
217B	EA	EA		NOP	
217D	A5	41		LDA	
217F	OA	OA		ASLA	
2181	BO	FO		BCS	
2183	EA	EA		NOP	
2185	rC	AO	21	JMP	jump to alAO if first number is neg
2188	A5	41		LDA	
218A	OA	OA		ASLA	adjust one to highest bit of the first number for one if it is positive
218C	BO	12		BCS	
218E	EA	EA		NOP	
2190	06	40		ASL	
2192	26	41		ROL	
2194	C6	42		DEC	
2196	A5	41		LDA	
2198	OA	OA		ASLA	
219A	90	F4		BCC	branch to 2190 if one to highest bit of first number is not one
219C	EA	EA		NOP	
219E	EA	EA		NOP	
21A0	A5	44		LDA	test the sign of the second number
21A2	OA			ASLA	
21A3	90	15		BCC	branch to 21BA if it is positive
21A5	A5	44		LDA	
21A7	OA			LSLA	adjust bit 14 of the second number for 0 if it is negative
21A8	OA			LSLA	
21A9	90	OC		BCC	
21AB	06	43		ASL	
21AD	26	44		ROL	
21AF	C6	45		DEC	
21B1	A5	44		LDA	
21B3	OA			ASLA	
21B4	OA			ASLA	
21B5	BO	F4		BCS	branch to 24AB if bit 14 is one
21B7	4C	CE	21	JMP	
21BA	A5	44		CDA	adjust bit 14 of the second number for 1 if it is positive
21BC	OA			ASLA	
21BD	OA			ASLA	
21BE	BO	OE		BCS	
21CO	EA	EA		NOP	

ADDITION SUBROUTINE - CONTINUED

21C2	06	43		ASL	
21C4	26	44		ROL	
21C6	C6	45		DEC	
21C8	A5	44		CDA	
21CA	0A	0A		ASLA	
21CC	90	F4		BCC	
21CE	A5	42		CDA	
21D0	C5	45		CMP	compare the exponents of two numbers
21D2	F0	11		BEQ	branch to 21ES if equal
21D4	10	12		BPL	branch to s1E8 if exp. of first number greater than second exp.
21D6	A5	41		LDA	
21D8	0A			ASLA	
21D9	66	41		ROR	
21DB	66	40		ROR	
21DD	E6	42		INC	
21DF	A5	42		LDA	
21E1	C5	45		CMP	
21E3	30	F1		BMI	
21E5	4C	FE	21	JMP	
21E8	18			CLC	
21E9	A5	44		CDA	adjust two numbers for equal exp.
21EB	EA	EA		NOP	
21ED	0A			ASLA	
21EE	66	44		ROR	
21F0	66	re		ROR	
21F2	E6	45		Inc	
21F4	A5	42		LDA	
21F6	C5	45		CMP	
21F8	D0	EE		BNE	
21FA	EA	EA		NOP	
21FC	EA	EA		NOP	
21FE	A5	42		LDA	store exp. of the result
2200	85	38		STA	
2202	D8			CLD	
2203	A5	40		CDA	add low bytes of two numbers
2205	18			CLC	
2206	65	43		ADC	
2208	85	36		STA	
220A	A5	41		CDA	add high bytes of two numbers
220C	65	44		ADC	
220E	85	37		STA	
2210	50	0F		BVC	branch to 2221 if overflow is clear
2212	EA	EA		NOP	
2214	EA			NOP	
2215	66	37		ROR	adjust result if overflow is set
2217	66	36		ROR	
2219	E6	38		INC	

ADDITION SUBROUTINE - Continued

221B	EA	EA		NOP	
221D	EA	EA		NOP	
221F	EA	EA		NOP	
2221	60			RTS	return from subroutine
2222	EA	EA		NOP	
2224	EA	EA		NOP	
2226	A5	33		LDA	test low byte of the second number
2228	DO	04		BNE	branch to 2150 if not zero
222A	A5	34		CDA	test high byte of the second number
222C	F0	04		BEQ	test high byte of the second number
222E	4C	50	21	JMP	branch to 2232 if zero
2231	EA			NOP	
2232	A5	30		LDA	set result equal to first number if second number is zero
2234	85	36		STA	
2236	A5	31		LDA	
2238	85	37		STA	
223A	A5	32		LDA	
223C	85	38		STA	
223E	4C	21	22	JMP	jump to return from subroutine
2241	A5	33		LDA	
2243	85	36		STA	set result equal to second number
2245	A5	34		LDA	if first number is zero
2247	85	37		STA	
2249	A5	35		LDA	
224B	85	38		STA	
224D	4C	21	22	JMP	jump to return from subroutine

SUBTRACTION SUBROUTINE

25B0	38			SEC	
25B1	A9	00		LDA	find 2's complement of second number
25B3	E5	33		SBC	
25B5	85	33		STA	
25B7	A9	00		LDA	
25B9	E5	34		SBC	
25BB	85	34		STA	
25BD	4C	40	21	JMP	jump to addition subroutine
25C0	EA			NOP	
25C1	EA			NOP	
25C2	EA			NOP	

DISPLAY PROGRAM

2490	A5	2d		LDA-ze	load high byte of rpm
2492	85	FB		STA-ze	
2494	A5	2C		LDA-ze	load low byte of rpm
2496	85	FA		STA-ze	
2498	A5	EE		LDA-ze	load adjusted injection pulse
249A	85	F9		STA-ze	
249C	A9	FF		LDA-#	
249E	8D	43	17	STA-Ab	
24A1	A9	7F		LDA-#	
24A3	8D	41	17	STA-Ab	
24A6	A2	09		LDX-#	
24A8	A0	03		LDY-#	
24AA	B9	F8	00	LDA(Y)	load accumulator with 00F8+Y
24AD	4A			LSR-A	
24AE	4A			LSR-A	
24AF	4A			LSR-A	
24B0	4A			LSR-A	
24B1	20	48	1F	JSR	jump to 1F48
24B4	B9	F8	99	LDA(Y)	load accumulator with 00F8+Y
24B7	29	0F		AND#	
24B9	20	48	1F		jump to 1F48
24BC	88			DEY	
24BD	D0	EB		BNE	branch to 24A8 if Y-reg is negative
24BF	EA			NOP	
24C0	4C	50	02	JMP	jump to injection program

DATA RECORDING PROGRAM

2900	A2	02		LDX	
2902	B5	8C		LDA,Xze	
2904	9D	99	39	SAX-Abs	store counts of rpm in memory locations 3000 to 3258
2907	CA			DEX	
2908	10	F8		BPL	
290A	18			CLC	
290B	AD	05	29	LDA-Abs	
290E	69	03		ADC#	
2910	0D	05	29	STA-Abs	
2913	AD	06	29	LDA-Abs	
2916	69	00		ADC#	
2918	8D	06	29	STA-Abs	
291B	38			SEC	
291C	AD	05	29	CDA-Abs	test end of rpm memory location
291F	E9	58		SBC#	
2921	AD	06	29	LDA-Abs	
2924	E9	32		SBC#	
2926	30	0A		BMI	branch to 2932 if rpm location is filled

DATA RECORDING PROGRAM - Continued

2928	A9	00		LDA#	
292A	8D	05	29	STA-ze	store rpm from location 3000 if all rpm location is filled
292D	A9	30		LDA#	
292F	8D	06	29	STA-ze	
2932	EA			NOP	
2933	EA			NOP	
293r	EA			NOP	
2935	A2	02		LDX	
2937	B5	AD		LDA,X-ze	
2939	90	60	32	STA,X-Abs	store counts of spark advance inlocations 3260 to 34B8
293C	CA			DEX	
293D	10	F8		BPL	
293F	18			CLC	
2940	AD	3A	29	LDA-Abs	
2943	69	03		ADC#	
2945	8D	3A	29	STA-Abs	
2948	AD	3B	29	LDA-Abs	
294B	69	00		ADC#	
294D	8D	3B	29	STA-Abs	
2950	38			SEC	
2951	AD	3A	29	LDA-Abs	test the end of spark advance memory locations.
2954	E9	B8		SBC#	
2956	AD	3B	29	LDA-Abs	
2959	E9	34		SBC#	
295B	30	0A		BMI	branch to 2967 if spark advance memory locations is not filled
295D	A9	60		LDA#	
295F	8D	8A	29	STA-ABS	store spark advance from 3260 if all locations are filled
2962	A9	32		LDA-#	
2964	8D	3B	29	STA-Abs	
2967	EA			NOP	
2968	EA			NOP	
2969	EA			NOP	
296A	A2	02		LDX-#	
296C	B5	B3		LDA,X-ze	
296E	9D	C9	34	STA,X-Abs	store counts of ignition time in memory locations 34C0 to 3718
2971	CA			DEX	
2972	10	F8		DPL	
2974	18			CLC	
2975	AD	6F	29	LDA-Abs	
2978	69	03		ADC-#	
297A	8D	6F	29	STA,Abs	
297D	AD	70	29	LDA,Abs	
2970	69	00		ADC-#	

DATA RECORDING PROGRAM - Continued

2982	8D	70	29	STA,Abs	
2985	38			SEC	
2986	AD	6F	29	LDA-Abs	test the end of ignition time memory location
2989	E9	18		SBC-#	
298B	AD	70	29	LDA,Abs	
298E	E9	37		SBC-#	
2980	30	0A		BMI	branch to 299C if ignition time location is not filled
2992	A9	C0		LDA-#	
2994	8D	6F	29	STA,Abs	store counts of ignition time from 34C0 if locations is filled
2997	A9	34		CDA-#	
2999	8D	70	29	STA,Abs	
299C	EA			NOP	
299D	EA			NOP	
299E	EA			NOP	
299F	A2	02		LDX-#	
29A1	B5	86		LDA,X-ze	
29A3	90	20	37	STA,Z-Abs	store counts of air flow rate in memory locations 3720 to 3978
29A6	CA			DEX	
29A7	10	F8		BPL	
29A9	18			CLC	
29AA	AD	A4	29	LDA-Abs	
29AD	69	03		ADC-#	
29AF	8D	A4	29	STA,Abs	
29B2	AD	A5	29	LDA-Abs	
29B5	69	00		ADC-#	
29B7	8D	A5	29	STA-Abs	
29BA	38			SEC	
29BB	AD	A4	29	LDA-Abs	test the end of air flow counts memory locations
29BE	E9	78		SBC-#	
29C9	AD	A5	29	LDA-Abs	
29C3	E9	39		SBC-#	
29C5	30	0A		BMI	branch to 29D1 if air flow memory locations is filled
29C7	A9	20		LDA-#	
29C9	8D	A5	29	STA-Abs	store counts of air flow from location 3720
29CC	A9	37		CDA-#	
29CE	8D	A5	29	STA-Abs	
29D1	EA			NOP	
29D2	EA			NOP	
29D3	EA			NOP	
29D4	A2	02		LDX-#	
29D6	B5	10		LDA,X-ze	
29D8	90	80	39	STA,X-Abs	store counts of ignition time in memory locations 3980 to 3BD8

DATA RECORDING PROGRAM -Continued

29D8	90	80	39	STA,X-Abs	store counts of ignition time in memory locations 3980 to 3BD8
29DB	CA			DEX	
29DC	10	F8		BPL	
29DE	18			CLC	
29DF	AD	D9	29	LDA,Abs	
29E2	69	03		ADC	
29E4	8D	D9	29	STA-Abs	
29E7	AD	DA	29	CDA-Abs	
29EA	69	00		ADC	
29EC	8D	Da	29	STA,Abs	
29EF	38			SEC	
29F0	AD	D9	29	CDA-Abs	test the end of ignition time counts location
29F3	E9	D8		SBC-#	
29F5	AD	DA	29	LDA,Abs	
29F8	E9	3B		SBC-#	
29FA	30	OA		BMI	branch to 2A06 if locations of ignition time count are filled
29FC	A9	80		LDA-#	
29FE	8D	D9	29	STA, Abs	
2A01	A9	39		LDA-#	
2A03	8D	DA	29	STA,Abs	
2A06	EA			NOP	
2A07	EA			NOP	
2A08	EA			NOP	
2A09	A5	EE		LDA-ze	
2A0B	8D	E0	3B	STA-Abs	store counts of injection pulse in memory locations 3BE0 to 3CA8
2A0E	AD	OC	2A	LDA-Abs	
2A11	69	01		ADC	
2A13	8D	OC	2A	STA-Abs	
2A16	AD	OD	2A	LDA-Abs	
2A19	69	00		ADC	
2A1E	38			SEC	
2A1F	AD	OC	2A	LDA-Abs	test the end of injection pulse location
2A22	E9	A8		SBC-#	
2A24	AD	OD	2A	LDA-ze	
2A27	E9	3C		SBC-#	
2A29	30	OA		BMI	branch to 2A35 if locations are not filled
2A2B	A9	EO		LDA-#	
2A2D	8D	OC	2A	STA-ze	
2A30	A9	3B		CDA-#	store counts of injection pulse from the location 3BEO

DATA RECORDING PROGRAM - Continued

2A32	8D	OD	2A	STA,ze	
2A35	EA			NOP	
2A36	EA			NOP	
2A37	EA			NOP	
2A38	4C	3D	28	JMP	
2A3B	EA			NOP	

MEAN CALCULATION PROGRAM (RPM)

2A50	A2	02		LDX	call the first number
2A52	BD	00	30	LDA,X-Abs	
2A55	95	30		STA,X-ze	
2A57	CA			DEX	
2A58	10	F8		DPL	
2A5A	A2	02		LDX	call the second number
2A5C	BD	03	30	LDA,X-Abs	
2A5F	95	33		STA,X-ze	
2A61	CA			DEX	
2A62	10	F8		BPL	
2A64	20	40	21	JSR	jump to addition subroutine to add two numbers
2A67	A2	02		LDA	
2A69	B5	36		LDA,X-ze	
2A6B	95	30		STA,X-ze	
2A6D	CA			DEX	
2A6E	10	F9		BPL	
2A70	A2	02		LDX	call the third number
2A72	BD	06	30	LDA,X-Abs	
2A75	95	33		STA,X-ze	
2A77	CA			DEX	
2A78	10	F8		BPL	
2A7A	20	40	21	JSR	jump to addition subroutine to fine sum of first three numbers
2A7D	18			CLC	
2A7E	AD	73	2A	LDA,Abs	
2A81	69	03		ADC-#	adjust to find sum of the total numbers
2A83	8D	73	2A	STA-Abs	
2A86	AD	74	2A	LDA-Abs	
2A89	69	00		ADC-#	
2A8B	8D	74	2A	STA-Abs	
2A8E	38			SEC	test if all numbers are added
2A8F	AD	73	2A	CDA-Abs	
2A92	E9	58		SBC-E	
2A94	AD	74	2A	LDA-Abs	
2A97	E9	32		SBC-#	
2A99	30	DC		BMI	branch to 2A67 if all numbers are not added

MEAN CALCULATION PROGRAM (RPM) - Continued

```
2A9b     A2     02              LDX
2A9D     B5     36              LDA,X-ze load sum of the total number into
                                           the dividend of divide subroutine
2A9F     95     0A              STA,X-ze
2AA2     CA                     DEX
2AA3     10     F9              BPL
2AA5     A9     00              LDA-#    load number of values into the
                                           divisor of divide subroutine
2AA7     85     OD              STA-ze
2AA9     A9     4B              LDA-#
2AAB     85     OE              STA-ze
2AAD     A9     FA              LDA-#
2AAF     85     OF              STA-ze
2AB1     20     00      25      JSR      jump to the divide subroutine
2AB4     A2     02              LDX
2AB6     B5     10              LDA,Xze  store result of the mean in the
                                           proper register
2AB8     9D     5A      32      STA,X-Abs
2ABB     CA                     DEX
2ABA     10     F9              CDA-#
2ABC     60                     RTS      return from the subroutine
```

STANDARD DIVIATION CALCULATION PROGRAM (RPM)

```
2C00     A2     02              LDX
2C02     BD     00      30      LDA,X-Abs compute difference of first
                                            number x, and mean x̄, or (x1-x̄)
2C05     95     30              STA,X-ze
2C07     CA                     DEX
2C08     10     F8              DPL
2C0A     A2     02              LDX
2C0C     BD     5A      32      CDA,Z-Abs
2C0F     95     33              STA,X-ze
2C11     CA                     DEX
2C12     10     F8              DPL
2C14     20     BO      25      JSR      jump to subtraction subroutine
2C17     A2     02              LDX
2C19     B5     36              LDA,X-ze compute result of (x1-x̄)^2
2C1B     95     01              STA,X-ze
2C1D     95     04              STA,X-ze
2C1F     CA                     DEX
2C20     10     F7              BPL
2C22     20     00      20      JSR      jump to multiplication subroutine
2C25     A2     02              LDX
2C27     B5     26              LDA,X-ze store result of (x.-x̄)^2 in a
                                            register
2C29     95     B6              STA,X-ze
```

STANDARD DIVIATION CALCULATION PROGRAM (RPM) - Continued

2C2B	CA			DEX	
2C2C	10	F9		BPL	
2C2E	A2	02		LDX	
2C30	BD	03	30	LDA,X-Abs	compute difference of second number x_2 and mean $\bar{x}$ or $(x_2-\bar{x})$
2C33	95	30		STA,X-ze	
2C35	CA			DEX	
2C36	10	F8		BPL	
2C38	A2	02		LDX	
2C3A	BD	5A	32	LDA,X-Abs	
2C3D	95	33		STA,X-ze	
2C3F	CA			DEX	
2C40	10	F9		DPL	
2C42	20	BO	25	JSR	jump to subtraction subroutine
2C45	A2	02		LDX	
2C47	B5	36		LDA,X-ze	compute result of $(x_2-\bar{x})^2$
2C49	95	01		STA,X-ze	
2C4B	95	04		STA,X-ze	
2C4D	CA			DEX	
2C4E	10	F7		BPL	
2C50	20	00	20	JSR	jump to multiply subroutine
2C53	A2	02		LDX	
2C55	B5	26		LDA,X-ze	compute sum of $(x_1-\bar{x})^2+(x_2-\bar{x})^2$
2C57	95	30		STA,X-ze	
2C59	CA			DEX	
2C5A	10	F9		PL	
2C5C	A2	02		LDX	
2C5E	B5	B6		LDA,X-ze	
2C60	95	33		STA,X-ze	
2C62	CA			DEX	
2C63	10	F9		BPL	
2C65	20	40	21	JSR	jump to the addition subroutine
2C68	A2	02		LDX	
2C6A	B5	36		LDA,X-ze	store result of $9x_1-\bar{x})^2+(x_2-\bar{x})^2$ in a register
2C6C	95	B6		STA,X-ze	
2C6E	CA			DEX	
2C6F	10	F9		BPL	
2C71	18			CLC	
2C72	AD	31	2C	CDA,Z-Abs	adjust to compute Sum $(x_i-\bar{x})^2$
2C75	69	03		ADC-ze	
2C77	8D	31	2C	STA,X-Abs	
2C7A	AD	32	2C	LDA,X-Abs	
2C7D	69	00		ADC-ze	
2C7F	8D	32	2C	STA,X-Abs	
2C82	38			SEC	
2C83	AD	31	2C	LDA,X-Abs	test if $x_i = x_n$
2C86	E9	58		SBC-ze	
2C88	AD	32	2C	LDA,X-Abs	

STANDARD DIVIATION CALCULATION PROGRAM (RPM) - Continued

2C8B	E9	32		SBC-ze	
2C8D	30	9F		BMI	branch to 2C2E if x_i x_n
2C8F	A2	02		LDX	
2C91	B5	B6		LDA,X-ze	load sum $(x_i-\bar{x})^2$ into the dividend of the divide subroutine
2C93	95	OA		STA,X-ze	
2C95	CA			DEX	
2C96	10	F9		BPL	
2C98	A9	CO		LDA-#	load value of (n-1) into the divisor of the divide subroutine
2C9A	85	OD		STA-ze	
2C9C	A9	4A		LDA-#	
2C9E	85	OE		STA-ze	
2CA0	A9	FA		LDA-#	
2CA2	85	OF		STA-ze	
2CA4	20	00	25	JSR	jump to the divide subroutine
2CA7	A2	02		LDX	
2CA9	B5	10		LDA,X-ze	store the result of standard divistion in a proper subroutine
2CAB	9D	5D	32	STA,X-Abs	
2CAE	CA			DEX	
2CAF	10	F9		BPL	
2CB1	60			RTS	return from the subroutine

APPENDIX G

DETAILED CIRCUIT DIAGRAMS

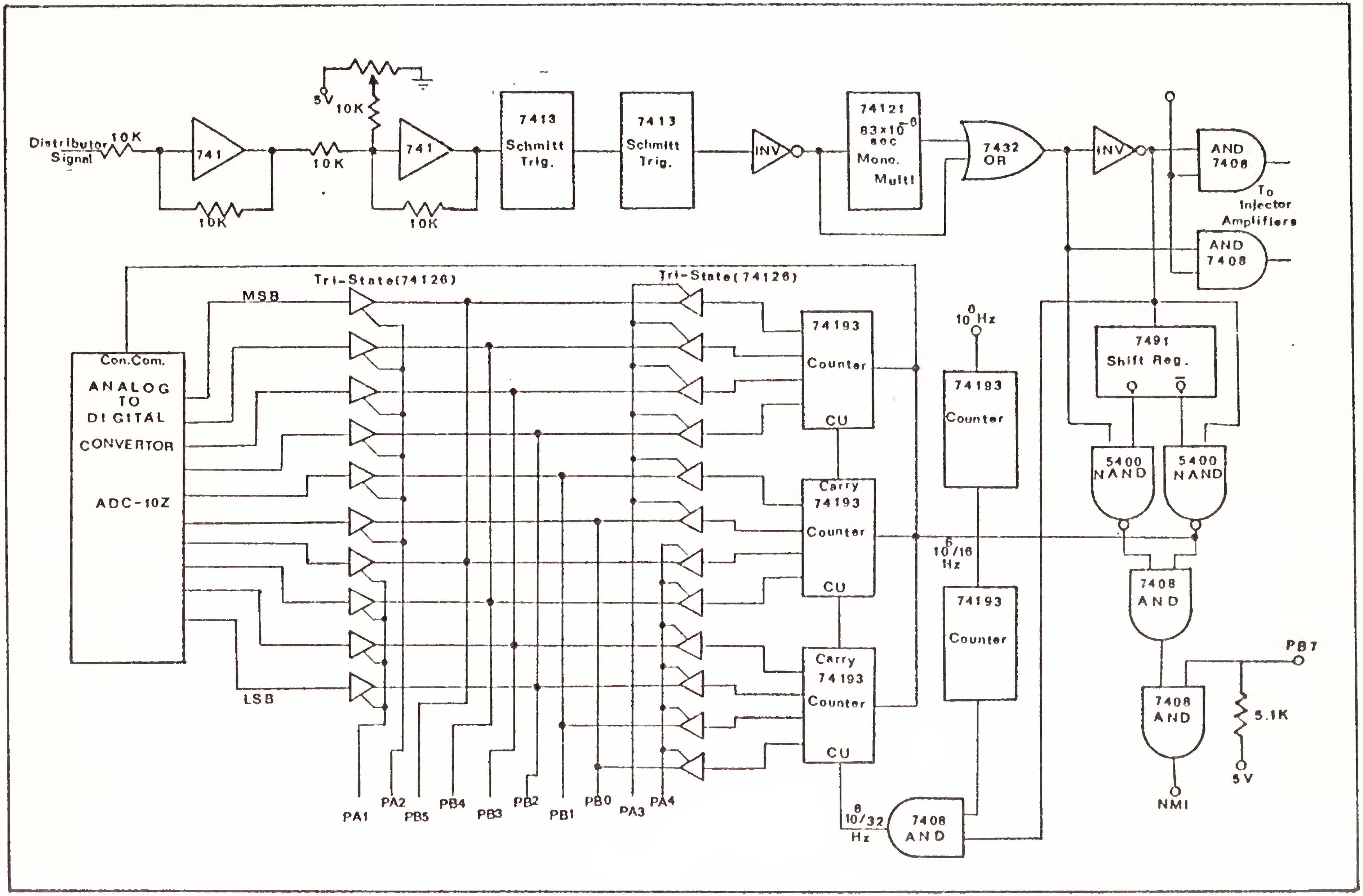

Figure G1. TTL Peripheral Circuitry for The Air-Fuel Controller System

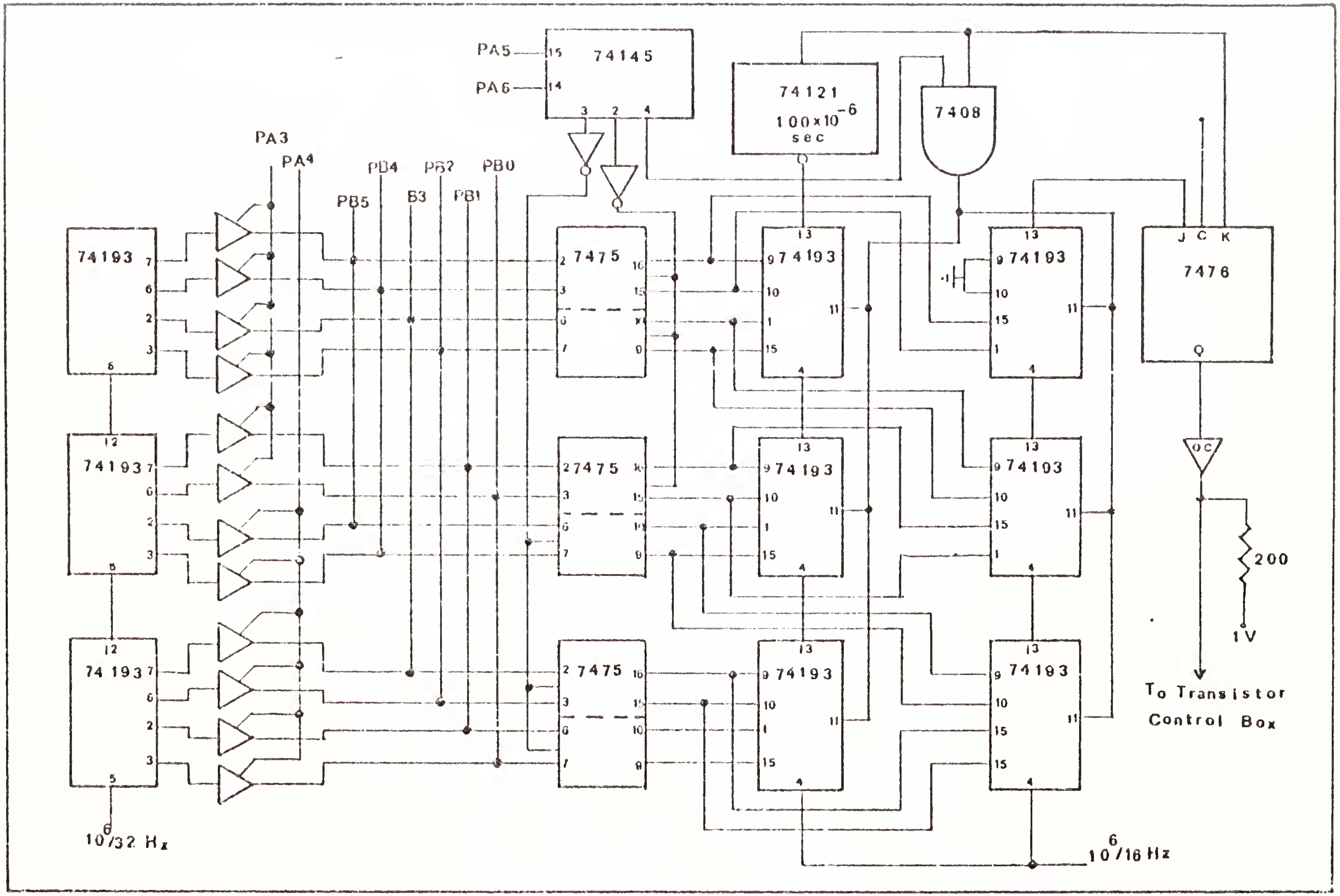

Figure G-2. TTL Circuitry (Peripheral) for The Ignition Time Controller System.

APPENDIX H

LIST OF DATA FOR AIR-FUEL RATIO TESTING

LIST OF DATA (BOSCH SYSTEM)

SPEED RPM	LOAD FT-LB	AFS V	PMN in-H_2O	TDB °F	TWB °F	ATMPR in-Hg	INJPU MIC-SEC	DELGAS LB	DELTIM SEC	PW PSIA	DENAIR LB/FT^3	CVM FT^3/MIN	AMFR LB/MIN	MFPM LB/MIN	AFT RESULT
1193	25.0	2.93	.054	81.4	64.0	28.85	3681.3	.40	408.4	.29497	.07040	14.7786	1.0404	.05876	17.71
1191	25.0	2.93	.053	81.4	64.0	28.85	3698.3	.40	407.8	.29497	.07040	14.6855	1.0339	.05885	17.57
1198	25.0	2.93	.053	81.4	64.0	28.85	3700.0	.40	409.4	.29497	.07040	14.6855	1.0339	.05862	17.63
1187	25.0	2.93	.053	81.4	64.0	28.85	3667.7	.40	423.3	.29497	.07040	14.6855	1.0339	.05670	18.23
1205	25.0	2.96	.053	81.4	64.0	28.85	3697.3	.40	388.4	.29497	.07040	14.6855	1.0339	.06178	16.73
2037	25.1	4.22	.133	81.5	66.0	28.85	3252.0	.40	251.6	.31626	.07033	23.3494	1.6421	.09540	17.21
2042	25.1	4.22	.133	81.5	66.0	28.85	3251.7	.40	243.9	.31626	.07033	23.3143	1.6397	.09841	16.66
2035	25.1	4.22	.131	81.5	66.0	28.85	3253.0	.40	251.5	.31626	.07033	23.1291	1.6267	.09541	17.05
2028	25.1	4.20	.130	81.5	66.0	28.85	3293.7	.40	238.7	.31626	.07033	23.0405	1.6204	.01005	16.12
2018	25.1	4.19	.130	81.5	66.0	28.85	3296.0	.40	251.1	.31626	.07033	23.0405	1.6204	.09559	16.95
2837	25.1	5.39	.248	82.0	64.0	28.88	3373.5	.40	168.3	.29497	.07033	31.8520	2.2401	.14264	15.70
2847	25.0	5.39	.247	82.0	64.0	28.88	3377.0	.40	175.5	.29497	.07033	31.7876	2.2356	.1367	16.35
2822	25.0	5.37	.239	82.0	64.0	28.88	3377.0	.40	161.5	.29497	.07033	31.2671	2.1990	.1486	14.80
2817	25.1	5.36	.237	82.0	64.0	28.88	3377.0	.40	167.3	.29497	.07033	31.1521	2.1909	.1435	15.27
2825	25.0	5.37	.237	82.0	64.0	28.88	3375.6	.40	172.1	.29497	.07033	31.1356	2.1898	.1394	15.70
1250	40.0	3.70	.115	78.0	62.0	28.76	4273.0	.40	286.1	.27494	.07057	21.6291	1.5264	.0839	18.19
1250	40.0	3.69	.113	78.0	62.0	28.76	4273.0	.40	274.2	.27494	.07057	21.4396	1.5131	.0875	17.28
1255	40.1	3.69	.107	78.0	62.0	28.76	4273.0	.40	276.1	.27494	.07057	20.9099	1.4757	.0869	16.98
1240	39.9	3.70	.105	78.0	62.0	28.76	4273.0	.40	273.7	.27494	.07057	20.6646	1.4584	.0877	16.63
1235	39.9	3.70	.102	78.0	62.0	28.76	4274.0	.40	276.7	.27494	.07057	20.3665	1.4373	.0860	16.71
2055	40.0	5.39	.254	78.0	63.0	28.76	4149.0	.40	179.9	.28495	.07050	32.1867	2.2706	.1334	17.03
2050	40.0	5.39	.254	78.0	63.0	28.76	4149.0	.40	175.5	.28495	.07057	32.1867	2.2706	.1367	16.61
2045	40.0	5.39	.255	78.0	63.0	28.76	4150.0	.40	179.8	.28495	.07057	32.2502	2.2751	.1335	17.04
2050	40.1	5.39	.255	78.0	63.0	28.76	4149.0	.40	180.5	.28495	.07057	32.2502	2.2751	.1330	17.11
2055	40.1	5.39	.255	78.0	63.0	28.76	4150.0	.40	171.8	.28495	.07057	32.2502	2.2751	.1396	16.29
2840	40.0	6.18	.488	79.0	63.0	28.76	4148.0	.40	112.2	.28495	.07042	44.6931	3.1474	.2139	14.72
2810	40.0	6.16	.470	79.0	63.0	28.76	4149.0	.40	120.1	.28495	.07042	43.8588	3.0887	.1999	15.46
2805	40.0	6.15	.471	79.0	63.0	28.76	4150.0	.40	116.9	.28495	.07042	43.9056	3.0920	.2053	15.06
2810	40.0	6.15	.472	79.0	63.0	28.76	4150.0	.40	122.7	.28495	.07042	43.9523	3.0953	.1956	15.82
2810	40.0	6.14	.472	79.0	63.0	28.76	4150.0	.40	123.7	.28495	.07042	43.9523	3.0953	.2000	15.48

LIST OF DATA (AIR-FUEL RATIO 14-1) FINAL

SPEED RPM	LOAD FT-LB	AFS VOL	PMN in-H_2O	TDB °F	TWB °F	ATMPR in-Hg	INJPU MIC-SEC	DELGAS LB	DELTIM SEC	PW PSIA	DENAIR	CFM FT^3/MIN	AMFR LB/MIN	MFPM LB/min	AFR RESULT
1265	10.1	2.24	.027	61.0	46.0	29.23	3218	.40	451.69	.15314	.07431	10.1922	.7573	.05313	14.25
1240	10.1	2.23	.026	61.0	46.0	29.23	3318	.40	467.78	.15314	.07431	10.0011	.7432	.05131	14.48
1265	10.1	2.24	.026	61.0	46.0	29.23	3316	.40	453.72	.15314	.07431	10.0011	.7432	.05290	14.05
1250	10.1	2.24	.026	61.0	46.0	29.23	3318	.40	452.70	.15314	.07431	10.0011	.7432	.05301	14.02
1260	10.1	2.24	.026	61.0	46.0	29.23	3317	.40	453.51	.15314	.07431	10.0011	.7432	.05292	14.04
2005	10.0	3.06	.054	70.0	50.0	29.23	3124	.40	312.88	.17796	.07305	14.5520	1.0630	.07671	13.86
1995	10.0	3.07	.054	70.0	50.0	29.23	3124	.40	298.41	.17796	.07305	14.5520	1.0630	.08043	13.22
1985	10.0	3.07	.054	70.0	50.0	29.23	3124	.40	294.30	.17796	.07305	14.5520	1.0630	.08155	13.03
1995	10.0	3.07	.054	70.0	50.0	29.23	3124	.40	298.02	.17796	.07305	14.5520	1.0630	.08053	13.20
1990	10.0	3.07	.054	70.0	50.0	29.23	3124	.40	305.52	.17796	.07305	14.5520	1.0630	.07855	13.53
2840	10.1	4.25	.127	79.0	54.0	29.23	3061	.40	193.31	.20625	.07183	22.5333	1.6184	.12415	13.04
2845	10.2	4.25	.127	79.0	54.0	29.23	3061	.40	204.92	.20625	.07183	22.5333	1.6184	.11712	13.82
2845	10.2	4.25	.127	79.0	54.0	29.23	3063	.40	200.08	.20625	.07183	22.5333	1.6184	.11995	13.49
2850	10.2	4.24	.127	79.0	54.0	29.23	3061	.40	198.38	.20625	.07183	22.5333	1.6184	.12098	13.38
2845	10.2	4.25	.127	79.0	54.0	29.23	3062	.40	199.40	.20625	.07183	22.5333	1.6184	.12036	13.45
1240	25.0	3.03	.052	80.0	66.0	28.85	4341	.40	327.77	.31626	.07043	14.5423	1.0243	.07322	13.99
1230	25.0	3.03	.052	80.0	66.0	28.85	4340	.40	331.19	.31626	.07043	14.5423	1.0243	.07247	14.13
1230	25.0	3.03	.052	80.0	66.0	28.85	4342	.40	326.58	.31626	.07043	14.5423	1.0243	.07349	13.94
1235	25.0	3.03	.052	80.0	66.0	28.85	4341	.40	325.48	.31626	.07043	14.5423	1.0243	.07374	13.89
1230	25.0	3.03	.052	80.0	66.0	28.85	4342	.40	325.37	.31626	.07043	14.5423	1.0243	.07376	13.89
2020	25.0	4.22	.116	82.0	67.0	28.85	3894	.40	224.47	.32757	.07016	21.7873	1.5286	.10692	14.30
2030	25.0	4.23	.117	82.0	67.0	28.85	3895	.40	215.08	.32757	.07016	21.8814	1.5352	.11159	13.76
2030	25.0	4.23	.117	82.0	67.0	28.85	3893	.40	212.61	.32757	.07016	21.8814	1.5352	.11288	13.60
2030	25.0	4.24	.115	82.0	67.0	28.85	3894	.40	225.54	.32757	.07016	21.6932	1.5220	.10641	14.30
2040	25.0	4.25	.114	82.0	67.0	28.85	3896	.40	222.06	.32757	.07016	21.5992	1.5154	.10808	14.02
2815	25.0	5.50	.256	81.0	67.0	28.85	4150	.40	143.55	.32757	.07028	32.3748	2.2753	.16219	13.61
2810	25.0	5.51	.256	81.0	67.0	28.85	4158	.40	145.58	.32757	.07028	32.3748	2.2753	.16486	13.80
2815	25.0	5.51	.256	81.0	67.0	28.85	4159	.40	147.46	.32757	.07028	32.3748	2.2753	.16276	13.98
2820	25.1	5.51	.256	81.0	67.0	28.85	4150	.40	142.72	.32757	.07028	32.3748	2.2753	.16816	13.53
2810	25.0	5.50	.255	81.0	67.0	28.85	4150	.40	148.57	.32757	.07028	32.2809	2.2687	.16154	14.04

LIST OF DATA (AIR-FUEL RATIO 14-1) FINAL

SPEED RPM	LOAD FT-LB	AFS VOL	PMN in-H_2O	TDB °F	TWB °F	ATMPR in-Hg	INJPU MIC-SEC	DELGAS LB	DELTIM SEC	PW PSIA	DENAIR	CFM FT^3/MIN	AMFR LB/MIN	MFPM LB/MIN	AFR RESULT
1285	40.0	3.74	.092	71.0	56.0	29.21	5045	.40	280.35	.22183	.07272	19.0512	1.3854	.08560	16.18
1267	40.0	3.73	.092	71.0	56.0	29.21	5140	.40	259.50	.22183	.07272	19.0512	1.3854	.09248	14.98
1245	40.0	3.74	.092	71.0	56.0	29.21	5172	.40	280.01	.22183	.07272	19.0512	1.3854	.08571	16.16
1227	40.0	3.72	.092	71.0	56.0	29.21	5175	.40	268.06	.22183	.07272	19.0512	1.3854	.08950	15.47
1220	40.0	3.71	.092	71.0	56.0	29.21	5174	.40	270.77	.22183	.07272	19.0512	1.3854	.08864	15.63
2000	40.0	5.37	.229	75.0	56.0	29.21	5170	.40	168.43	.22183	.07268	30.1028	2.1880	.14249	15.35
2007	40.1	5.36	.228	75.0	56.0	29.21	5139	.40	172.18	.22183	.07268	30.0368	2.1832	.13939	15.66
2016	40.1	5.36	.228	75.0	56.0	29.21	5140	.40	171.35	.22183	.07268	30.0368	2.1832	.14006	15.59
2015	40.1	5.36	.228	75.0	56.0	29.21	5108	.40	155.90	.22183	.07268	30.0368	2.1832	.15390	14.19
2015	40.1	5.36	.228	75.0	56.0	29.21	5107	.40	167.20	.22183	.07268	30.0368	2.1832	.14354	15.21
2855	40.0	6.30	.491	75.0	58.0	29.21	5171	.40	98.55	.23843	.07217	44.2839	3.1959	.24353	13.12
2845	40.1	6.30	.491	75.0	58.0	29.21	5171	.40	111.05	.23843	.07217	44.2839	3.1959	.21612	14.79
2845	40.2	6.39	.488	75.0	58.0	29.21	5172	.40	111.33	.23843	.07217	44.1481	3.1861	.21558	14.78
2860	40.1	6.30	.491	75.0	58.0	29.21	5172	.40	105.84	.23843	.07217	44.2839	3.1959	.22676	14.09
2860	40.2	6.30	.491	75.0	58.0	29.21	5172	.40	109.05	.23843	.07217	44.2839	3.1959	.22017	14.51

LIST OF DATA (AIR-FUEL RATIO 16-1) FINAL

SPEED RPM	LOAD FT-LB	AFS VOL	PMN in-H_2O	TDB °F	TWB °F	ATMPR in-Hg	INJPU MIC-SEC	DELGAS LB	DELTIM SEC	PW PSIA	DENAIR LB/FT^3	CFM FT^3/MIN	AMFR LB/MIN	MFPM LB/MIN	AFR RESULT
1270	10.0	2.27	.030	66.0	48.0	29.23	2997	.40	488.64	.16514	.07361	10.7961	.79468	.04912	16.18
1230	10.0	2.27	.029	66.0	48.0	29.23	2998	.40	493.10	.16514	.07361	10.6141	.78128	.04867	16.05
1230	10.0	2.24	.029	66.0	48.0	29.23	3124	.40	512.19	.16514	.07361	10.6141	.78128	.04686	16.67
1240	10.0	2.25	.029	66.0	48.0	29.23	3120	.40	497.13	.16514	.07361	10.6141	.78128	.04828	16.18
1220	10.0	2.27	.029	66.0	48.0	29.23	3020	.40	508.21	.16514	.07361	10.6141	.78128	.04722	16.54
2005	9.9	3.09	.056	70.0	49.0	29.23	2869	.40	340.79	.17155	.07361	14.8175	1.0827	.07042	15.37
1995	9.8	3.10	.057	70.0	49.0	29.23	2870	.40	341.47	.17155	.07361	14.9496	1.0923	.07028	15.54
2000	9.9	3.10	.057	70.0	49.0	29.23	2869	.40	336.09	.17155	.07361	14.9496	1.0923	.07141	15.29
2010	9.9	3.10	.057	70.0	49.0	29.23	2869	.40	339.19	.17155	.07361	14.9496	1.0923	.07075	15.44
2000	9.8	3.10	.056	70.0	49.0	29.23	2870	.40	340.12	.17155	.07361	14.8175	1.0827	.07056	15.34
2845	10.0	4.24	.127	73.0	50.0	29.23	2805	.40	233.55	.17796	.07267	22.4019	1.6279	.10276	15.84
2845	10.1	4.24	.127	73.0	50.0	29.23	2806	.40	228.65	.17796	.07267	22.4019	1.6279	.10496	15.51
2830	10.1	4.26	.126	73.0	50.0	29.23	2805	.40	230.90	.17796	.07267	22.3133	1.6214	.10394	15.60
2840	10.1	4.25	.126	73.0	50.0	29.23	2805	.40	234.15	.17796	.07267	22.3133	1.6214	.10250	15.82
2845	10.1	4.26	.127	73.0	50.0	29.23	2806	.40	230.24	.17796	.07267	22.4019	1.6279	.10424	15.62
1230	24.9	3.00	.050	79.0	66.0	28.85	3894	.40	350.38	.31626	.07056	14.2469	1.0052	.06849	14.67
1250	25.0	2.99	.049	79.0	66.0	28.85	3829	.40	359.85	.31626	.07056	14.1033	.99508	.06669	14.92
1250	25.0	2.98	.049	79.0	66.0	28.85	3828	.40	364.72	.31626	.07056	14.1034	.99508	.06580	15.12
1250	25.0	2.98	.049	79.0	66.0	28.85	3829	.40	367.17	.31626	.07056	14.1034	.99508	.05636	15.22
1175	24.9	2.83	.046	79.0	66.0	28.85	3828	.40	393.89	.31626	.07056	13.6636	.96405	.06093	15.82
2032	25.1	4.24	.113	80.0	64.0	29.19	3571	.40	244.61	.29497	.07133	21.3262	1.5212	.09811	15.50
2023	25.2	4.22	.114	80.0	64.0	29.19	3508	.40	248.54	.29497	.07133	21.4201	1.5279	.09656	15.82
2003	25.1	4.15	.112	80.0	64.0	29.19	3540	.40	247.09	.29497	.07133	21.2309	1.5144	.09713	15.59
2010	25.1	4.14	.116	80.0	64.0	29.19	3571	.40	243.35	.29497	.07133	21.2309	1.5413	.09862	15.62
2020	25.0	4.15	.117	80.0	64.0	29.19	3541	.40	249.04	.29497	.07133	21.7005	1.5479	.09637	16.06
2825	25.0	5.43	.254	79.0	63.0	29.19	3637	.40	170.13	.28432	.07149	31.9723	2.2857	.14107	16.20
2815	25.0	5.43	.254	79.0	63.0	29.19	3638	.40	169.00	.28432	.07149	31.9401	2.2834	.14201	16.07
2815	25.0	5.43	.252	79.0	63.0	29.19	3638	.40	160.99	.28432	.07149	31.8450	2.2766	.14908	15.27
2815	24.9	5.42	.251	79.0	63.0	29.19	3636	.40	158.71	.28432	.07149	31.7821	2.2721	.15122	15.02
2805	25.0	5.43	.250	79.0	63.0	29.19	3637	.40	149.98	.28432	.07149	31.6841	2.2651	.16002	14.15

LIST OF DATA (AIR-FUEL RATIO 16-1) FINAL

SPEED RPM	LOAD FT-LB	AFS VOL	PMN in-H_2O	TDB °F	TWB °F	ATMPR in-Hg	INJPU MIC-SEC	DELGAS LB	DELTIM SEC	PW PSIA	DENAIR	CFM FT^3/MIN	AMFR LB/MIN	MFPM LB/MIN	AFR RESULT
1280	40.0	4.02	.123	71.0	54.0	29.21	4748	.40	278.90	.20625	.07081	22.4900	1.59289	.08605	18.51
1275	40.0	4.01	.122	71.0	54.0	29.21	4790	.40	259.97	.20625	.07081	22.4036	1.58638	.09232	17.18
1210	40.0	3.79	.111	71.0	54.0	29.21	4851	.40	292.12	.20625	.07081	21.3670	1.51297	.08215	18.41
1220	40.0	3.84	.111	71.0	54.0	29.21	4854	.40	289.81	.20625	.07081	21.3670	1.51297	.08281	18.27
1220	40.0	3.85	.111	71.0	54.0	29.21	4850	.40	277.62	.20625	.07081	21.3670	1.51297	.08645	17.50
2000	40.0	5.46	.256	73.0	55.0	29.21	4734	.40	180.39	.21404	.07059	32.3034	2.28027	.13304	17.14
2010	39.8	5.45	.254	73.0	55.0	29.21	4724	.40	177.23	.21404	.07059	32.1767	2.27132	.13542	16.77
1995	40.0	5.44	.254	73.0	55.0	29.21	4724	.40	175.42	.21404	.07059	32.1767	2.27132	.13681	16.60
2010	39.9	5.46	.254	73.0	55.0	29.21	4725	.40	171.91	.21404	.07059	32.1767	2.27132	.13961	16.27
2010	39.9	5.46	.254	73.0	55.0	29.21	4725	.40	174.59	.21404	.07059	32.1767	2.27132	.13746	16.52
2880	40.0	6.36	.534	75.0	56.0	29.21	4724	.40	124.23	.22183	.07222	47.4960	3.4302	.19319	17.76
2885	40.0	6.36	.534	75.0	56.0	29.21	4725	.40	113.83	.22183	.07222	47.4960	3.4302	.21084	16.27
2900	40.0	6.37	.540	75.0	56.0	29.21	4726	.40	111.07	.22183	.07222	47.5802	3.4363	.21608	15.90
2835	40.0	6.31	.503	75.0	56.0	29.21	4728	.40	118.70	.22183	.07222	45.9973	3.3220	.20219	16.43
2830	40.0	6.30	.496	75.0	56.0	29.21	4660	.40	121.42	.22183	.07222	45.9973	3.3220	.19766	16.81

LIST DATA (AIR-FUEL RATIO 18-1) FINAL

SPEED RPM	LOAD FT-LB	AFS VOL	PMN in-H_2O	TDB °F	TWB °F	ATMPR in-Hg	INJPU MIC-SEC	DELGAS LB	DELTIM SEC	PW PSIA	DENAIR LB/FT^3	CFM FT^3/MIN	AMFR LB/MIN	MFPM LB/MIN	AFR RESULT
1200	10.0	2.44	.031	69.0	52.0	29.26	3125	.40	534.09	.19165	.07320	11.0054	.80564	.04494	17.93
1270	10.1	2.55	.034	69.0	52.0	29.26	3126	.40	516.49	.19165	.07320	11.5271	.84383	.04647	18.16
1240	10.1	2.57	.035	69.0	52.0	29.26	3190	.40	511.47	.19165	.07320	11.6958	.85618	.04692	18.25
1250	10.1	2.57	.035	69.0	52.0	29.26	3120	.40	520.38	.19165	.07320	11.6958	.85618	.04612	18.56
1230	10.1	2.50	.034	69.0	52.0	29.26	3140	.40	514.69	.19165	.07320	11.5271	.84383	.04663	18.10
2020	10.0	3.27	.066	70.0	49.0	29.23	2742	.40	348.02	.17155	.07307	16.0899	1.17570	.06703	17.54
2005	9.9	3.28	.066	70.0	49.0	29.23	2740	.40	343.47	.17155	.07307	16.0899	1.17570	.06987	16.83
2060	10.0	3.28	.066	70.0	49.0	29.23	2677	.40	344.81	.17155	.07307	16.0899	1.17570	.06961	16.89
2050	10.1	3.28	.066	70.0	49.0	29.23	2692	.40	349.82	.17155	.07307	16.0899	1.17570	.06861	17.14
2010	9.9	3.27	.066	70.0	49.0	29.23	2720	.40	351.27	.17155	.07307	16.0899	1.17570	.06832	17.21
2870	10.0	4.37	.145	70.0	52.0	29.23	2742	.40	244.12	.19165	.07300	23.8864	1.74373	.09831	17.74
2865	10.0	4.37	.146	70.0	52.0	29.23	2740	.40	237.46	.19165	.07300	23.9689	1.74975	.10107	17.31
2900	10.0	4.37	.146	70.0	52.0	29.23	2741	.40	240.09	.19165	.07300	23.9689	1.74975	.09996	17.50
2860	10.0	4.37	.146	70.0	52.0	29.23	2741	.40	242.53	.19165	.07300	23.9689	1.74975	.09896	17.68
2880	10.0	4.37	.146	70.0	52.0	29.23	2742	.40	238.95	.19165	.07300	23.8864	1.74373	.10044	17.36
1247	25.1	3.13	.060	83.0	67.0	28.80	3731	.40	386.27	.32757	.06992	15.6815	1.09649	.06213	17.65
1227	25.0	3.16	.061	83.0	67.0	28.80	3765	.40	380.30	.32757	.06992	15.8120	1.10562	.06311	17.52
1235	25.0	3.07	.054	83.0	67.0	28.80	3637	.40	371.45	.32757	.06992	14.8746	1.04007	.06461	16.10
1227	25.0	3.06	.075	83.0	67.0	28.80	3637	.40	382.81	.32757	.06992	17.5379	1.22630	.06269	19.56
1340	25.0	3.43	.061	83.0	67.0	28.80	3741	.40	355.28	.32757	.06992	15.7207	1.09924	.06755	16.27
2000	25.0	5.03	.189	79.0	68.0	28.55	3702	.40	224.57	.33889	.06975	27.9105	1.94686	.09813	18.21
2070	25.2	5.04	.195	79.0	68.0	28.55	3655	.40	226.56	.33889	.06975	28.3513	1.97761	.10593	18.67
1990	25.0	5.04	.190	79.0	68.0	28.55	3742	.40	237.81	.33889	.06975	27.9599	1.94996	.10092	18.32
2030	25.0	5.05	.193	79.0	68.0	28.55	3702	.40	217.94	.33889	.06975	28.2051	1.96740	.10086	19.55
2000	25.0	5.05	.195	79.0	68.0	28.55	3701	.40	217.71	.33889	.06975	28.3513	1.97761	.10096	19.94
2837	25.0	5.68	.310	83.0	68.0	28.55	3604	.40	167.26	.33889	.06927	35.8926	2.4866	.13837	17.97
2835	25.0	5.67	.309	83.0	68.0	28.55	3637	.40	167.26	.33889	.06927	35.8345	2.4826	.14359	17.30
2727	25.0	5.64	.303	83.0	68.0	28.55	3701	.40	176.13	.33889	.06927	35.4839	2.4583	.13626	18.04
2903	25.1	5.74	.326	83.0	68.0	28.55	3636	.40	167.02	.33889	.06927	36.8660	2.5541	.14370	17.77
2840	25.1	5.66	.305	83.0	68.0	28.55	3573	.40	175.01	.33889	.06927	35.6304	2.4684	.13713	18.00

LIST DATA (AIR-FUEL RATIO 18-1) FINAL

SPEED RPM	LOAD FT-LB	AFS VOL	PMN in-H_2O	TDB °F	TWB °F	ATMPR in-Hg	INJPU MIC-SEC	DELGAS LB	DELTIM SEC	PW PSIA	DENAIR LB/FT^3	CFM FT^3/MIN	AMRF LB/MIN	MFPM LB/MIN	AFR RESULT
1230	39.7	4.16	.130	78.0	62.0	28.76	4660	.40	272.61	.27494	.07057	24.0009	1.6232	.08804	18.44
1430	39.9	4.86	.162	78.0	62.0	28.76	4662	.40	267.43	.27494	.07057	25.6835	1.8125	.08974	20.20
1400	40.0	4.86	.161	78.0	62.0	28.76	4570	.40	266.78	.27494	.07057	25.6039	1.8069	.08996	20.08
1400	40.0	4.87	.163	78.0	62.0	28.76	4660	.40	272.17	.27494	.07057	25.7628	1.8181	.08818	20.62
1420	40.0	4.87	.163	78.0	62.0	28.76	4728	.40	256.89	.27494	.07057	25.7629	1.8181	.09342	19.46
2030	40.1	5.62	.288	79.0	62.0	28.76	4536	.40	188.73	.27494	.07045	34.3017	2.4167	.12716	19.00
2020	40.2	5.61	.286	79.0	62.0	28.76	4470	.40	191.89	.27494	.07045	34.1821	2.4082	.12507	19.25
2050	40.0	5.61	.286	79.0	62.0	28.76	4533	.40	188.61	.27494	.07045	34.1821	2.4082	.12725	18.92
2020	40.0	5.59	.281	79.0	62.0	28.76	4532	.40	187.04	.27494	.07045	33.8811	2.3870	.12831	18.60
2030	40.0	5.59	.281	79.0	62.0	28.76	4469	.40	188.20	.27494	.07045	33.8811	2.3870	.12752	18.72
2875	40.1	6.45	.580	79.0	63.0	28.76	4405	.40	121.86	.28495	.07042	48.7360	3.4321	.19695	17.43
2890	40.1	6.47	.588	79.0	63.0	28.76	4469	.40	126.38	.28495	.07042	49.0719	3.4558	.18990	18.20
2785	40.0	6.38	.537	79.0	63.0	28.76	4469	.40	137.06	.28495	.07042	46.8895	3.3021	.17510	18.86
2785	40.0	6.38	.537	79.0	63.0	28.76	4480	.40	139.38	.28495	.07042	46.8895	3.3021	.17219	19.18
2793	40.0	6.39	.541	79.0	63.0	28.76	4469	.40	139.15	.28495	.07042	47.0643	3.3144	.17247	19.22

LIST OF DATA (FIRST INJECTOR CALIBRATION)

AF	SPEED RPM	LOAD FT-LB	AFS VOL	PMN in-H_2O	TDB °F	TWB °F	ATMPR in-Hg	INJPU MIC-SEC	DELGAS LB	DELTIM SEC	PW PSIA	DENAIR LB/FT^3	CFM FT^3/MIN	AMRF LB/MIN	MFPM LB/MIN	AFR RESULT
14.	1225	24.9	3.07	.052	80.5	63.5	28.85	3777	.40	356.24	.28996	.07052	14.5332	1.0249	.06737	15.21
14.	1228	25.0	3.06	.052	80.5	63.5	28.85	3765	.40	330.61	.28996	.07052	14.5332	1.0249	.07259	14.12
14.	1225	25.0	3.04	.052	80.5	63.5	28.85	3765	.40	345.26	.28996	.07052	14.5332	1.0249	.06951	14.74
14.	1217	25.0	3.03	.052	80.5	63.5	28.85	3765	.40	351.82	.28996	.07052	14.4770	1.0210	.06280	16.26
14.	1219	25.0	3.02	.051	80.5	63.5	28.85	3764	.40	381.91	.28996	.07052	14.3923	1.0150	.06284	16.15
14.	2025	25.0	4.36	.134	83.0	66.0	28.85	3380	.40	248.76	.31626	.07015	23.4451	1.6447	.09648	17.05
14.	2015	25.0	4.30	.132	83.0	66.0	28.85	3380	.40	245.84	.31626	.07015	23.3063	1.6349	.09762	16.75
14.	2032	25.0	4.36	.137	83.0	66.0	28.85	3380	.40	255.99	.31626	.07015	23.6847	1.6615	.09375	17.72
14.	2017	25.1	4.28	.133	83.0	66.0	28.85	3378	.40	262.51	.31626	.07015	23.3793	1.6401	.09142	17.94
14.	1997	25.1	4.20	.131	83.0	66.0	28.85	3379	.40	263.62	.31626	.07015	23.1588	1.6246	.09104	17.84
14.	2821	25.1	5.46	.260	80.0	68.0	28.85	3444	.40	164.56	.33889	.07045	32.5885	2.2957	.14584	15.74
14.	2835	25.0	5.45	.260	80.0	68.0	28.85	3444	.40	181.83	.33889	.07045	32.5885	2.2947	.13199	17.39
14.	2798	25.0	5.41	.254	80.0	68.0	28.85	3422	.40	182.01	.33889	.07045	32.2092	2.2690	.13186	17.20
14.	2800	25.1	5.41	.251	80.0	68.0	28.85	3402	.40	182.46	.33889	.07045	32.0179	2.2555	.13153	17.14
14.	2795	25.1	5.41	.251	80.0	68.0	28.85	3380	.40	169.02	.33889	.07045	32.0179	2.2555	.14199	15.88
16.	1200	24.9	3.38	.061	67.0	49.0	29.26	3700	.40	405.29	.17155	.07351	15.4202	1.1335	.05922	19.14
16.	1240	24.9	3.38	.061	67.0	49.0	29.26	3637	.40	398.68	.17155	.07351	15.4202	1.1335	.06020	18.83
16.	1200	24.9	3.39	.065	67.0	49.0	29.26	3639	.40	431.10	.17155	.07351	15.9192	1.1702	.05567	21.02
16.	1210	24.9	3.38	.061	67.0	49.0	29.26	3638	.40	410.86	.17155	.07351	15.4202	1.1335	.05841	19.41
16.	1220	24.9	3.38	.061	67.0	49.0	29.26	3639	.40	420.31	.17155	.07351	15.4202	1.1335	.05710	19.85
16.	2030	25.1	5.17	.185	68.0	50.0	29.26	3574	.40	247.73	.17796	.07338	26.9200	1.9754	.09688	20.39
16.	2040	25.1	5.17	.185	68.0	50.0	29.26	3536	.40	244.03	.17796	.07338	25.4200	1.9754	.09835	20.08
16.	2030	25.1	5.17	.183	68.0	50.0	29.26	3574	.40	241.30	.17796	.07338	26.7737	1.9646	.09946	19.75
16.	2030	25.1	5.17	.185	68.0	50.0	29.26	3560	.40	243.66	.17796	.07338	26.4200	1.9754	.09850	20.05
16.	2030	25.1	5.17	.183	68.0	50.0	29.26	3550	.40	245.18	.17796	.07338	26.7737	1.9647	.09789	20.07
16.	2735	24.9	5.79	.324	68.0	50.0	29.26	3511	.40	188.54	.17796	.07338	35.6535	2.6162	.12729	20.55
16.	2780	24.9	5.84	.342	68.0	50.0	29.26	3572	.40	176.93	.17796	.07338	36.6333	2.6881	.13565	19.81
16.	2800	25.0	5.85	.345	68.0	50.0	29.26	3573	.40	164.31	.17796	.07338	36.7940	2.6999	.14606	18.48
16.	2790	25.0	5.84	.342	68.0	50.0	29.26	3550	.40	174.81	.17796	.07338	36.6333	2.6881	.13730	19.58
16.	2780	25.0	5.85	.345	68.0	50.0	29.26	3570	.40	180.03	.17796	.07338	36.7940	2.6999	.13331	20.25

LIST OF DATA (SECOND INJECTOR CALIBRATION)

AF	SPEED RPM	LOAD FT-LB	AFS VOL	PMN in-H_2O	TDB °F	TWB °F	ATMPR in-Hg	INJPU MIC-SEC	DELGAS LB	DELTIM SEC	PW PSIA	DENAIR LB/FT^3	CFM FT^3/MIN	AMRF LB/MIN	MFPM LB/MIN	ARF RESULT
14	1250	25.0	3.18	.058	67.0	51.0	29.26	3768	.40	381.97	.18481	.07348	15.0378	1.1050	.06283	17.59
14	1230	24.8	3.20	.058	67.0	51.0	29.26	3832	.40	384.12	.18481	.07348	15.0378	1.1050	.06248	17.69
14	1250	25.0	3.19	.058	67.0	51.0	29.26	3820	.40	379.98	.18481	.07348	15.0378	1.1050	.06316	17.49
14	1240	25.0	3.20	.058	67.0	51.0	29.26	3840	.40	382.15	.18481	.07348	15.0378	1.1050	.06280	17.59
14	1235	25.0	3.19	.058	67.0	51.0	29.26	3820	.40	380.32	.18481	.07348	15.0378	1.1050	.06310	17.51
14	2070	25.0	4.78	.157	69.0	51.0	29.26	3573	.40	243.42	.18405	.07322	24.8194	1.8174	.09859	18.43
14	2050	25.0	4.78	.148	69.0	51.0	29.26	3574	.40	229.36	.18405	.07322	24.0954	1.7644	.10464	16.86
14	2040	25.0	4.73	.147	69.0	51.0	29.26	3573	.40	243.13	.18405	.07322	24.0137	1.7584	.09871	17.81
14	2060	25.0	4.73	.147	69.0	51.0	29.26	3573	.40	239.62	.18405	.07322	24.0137	1.7584	.10016	17.56
14	2050	25.0	4.73	.147	69.0	51.0	29.26	3574	.40	245.20	.18405	.07322	24.0137	1.7584	.09788	17.96
14	2880	25.0	5.57	.274	68.0	50.0	29.26	3637	.40	163.23	.17796	.07338	32.7796	2.4053	.14703	16.36
14	2830	25.0	5.56	.274	68.0	50.0	29.26	3637	.40	161.95	.17796	.07338	32.7796	2.4053	.14819	16.23
14	2830	25.0	5.56	.273	68.0	50.0	29.26	3572	.40	165.56	.17796	.07338	32.7195	2.4009	.14496	16.56
14	2830	25.0	5.56	.273	68.0	50.0	29.26	3637	.40	162.83	.17796	.07338	32.7195	2.4009	.14739	16.29
14	2840	25.0	5.56	.273	68.0	50.0	29.26	3640	.40	164.51	.17796	.07338	32.7195	2.4009	.14589	16.46
16	1202	24.9	2.94	.031	79.0	61.0	28.88	3480	.40	425.35	.26303	.07078	11.1926	.7922	.05049	14.04
16	1212	25.0	3.11	.031	79.0	61.0	28.88	3520	.40	455.18	.26303	.07078	11.1926	.7922	.05027	14.97
16	1237	25.1	3.10	.031	79.0	61.0	28.88	3511	.40	404.14	.26303	.07078	11.1926	.7922	.05940	13.27
16	1223	25.1	3.05	.031	79.0	61.0	28.88	3470	.40	416.22	.26303	.07078	11.1926	.7922	.05766	13.74
16	1210	25.0	3.05	.031	79.0	61.0	28.88	3498	.40	421.68	.26303	.07078	11.1926	.7922	.05691	13.92
16	2037	25.0	4.66	.120	84.0	63.0	28.88	3263	.40	260.13	.28432	.07012	22.1656	1.5545	.09226	16.85
16	2007	25.0	4.61	.110	84.0	63.0	28.88	3331	.40	262.00	.28432	.07012	21.2194	1.4881	.09160	16.24
16	2012	25.1	4.44	.120	84.0	63.0	28.88	3221	.40	262.17	.28432	.07012	22.1660	1.5545	.09150	16.99
16	1983	25.0	4.35	.121	84.0	63.0	28.88	3223	.40	272.10	.28432	.07012	22.2860	1.5629	.08820	17.72
16	2045	25.0	4.53	.139	84.0	63.0	28.88	3253	.40	268.13	.28432	.07012	23.8870	1.6742	.08951	18.71
16	2795	25.0	5.48	.259	82.0	62.0	28.88	3255	.40	187.37	.27368	.07309	31.9600	2.3360	.12809	17.71
16	2802	25.0	5.49	.258	82.0	62.0	28.88	3316	.40	181.92	.27368	.07309	31.8450	2.3227	.13193	17.86
16	2805	25.1	5.49	.259	82.0	62.0	28.88	3253	.40	184.12	.27368	.07309	31.9310	2.3337	.13035	17.91
16	2810	25.1	5.49	.259	82.0	62.0	28.88	3252	.40	183.83	.27368	.07309	31.9620	2.3361	.13056	17.89
16	2817	25.0	5.49	.258	82.0	62.0	28.88	3252	.40	180.20	.27368	.07309	31.8692	2.3292	.13319	17.49

APPENDIX I

LIST OF DATA FOR SPARK IGNITION TESTING

LIST OF DATA FOR IGNITION SYSTEM

SPEED (RPM) DAYTRONIC	DISTRIB-UTOR CYCLE (MS) SCOPE	COMPUTED SPEED (RPM) FROM DIST	SPARK ADV BASED ON DIST (MS)	SPARK ADV BASED ON DIST (MS)	SPARK ADV ACTUAL (DEG CS)	DWELL (MS)	DWELL (DEG CS)
1015	116.0	1034.0	3.30	20.48	5.05	7.10	44.07
1030	116.0	1034.0	3.50	21.72	6.29	7.30	45.31
1010	116.0	1034.0	3.40	21.10	5.67	7.00	43.45
1010	120.0	1000.0	3.30	19.80	5.27	7.20	43.20
980	116.0	1034.0	3.20	19.86	4.37	7.10	44.07
910	131.0	916.0	3.40	18.69	3.43	7.50	41.22
1065	122.0	983.6	3.50	20.66	5.23	7.20	42.49
960	124.0	967.7	3.50	20.32	4.89	7.60	44.12
1015	122.0	983.6	3.14	18.53	3.10	7.50	44.26
1265	94.0	1276.6	3.75	28.72	13.29	6.0	45.96
1240	93.0	1290.3	3.85	29.81	14.38	6.0	45.47
2165	95.0	1263.2	3.60	27.28	11.85	6.0	45.47
2170	91.0	1318.7	3.65	28.88	13.45	5.5	43.52
1230	93.0	1290.3	3.90	30.19	14.76	6.0	46.45
1230	98.0	1224.5	3.80	27.92	12.49	6.1	44.45
2100	102.0	1176.5	3.70	26.11	10.68	6.0	42.35
2170	97.0	1237.1	3.75	28.57	13.14	6.1	44.90
1240	94.0	1276.6	3.65	27.96	12.53	6.0	45.96
1600	75.5	1589.4	3.84	36.61	21.18	4.7	44.82
1609	74.9	1602.1	3.93	37.78	22.35	4.8	46.14
1610	74.7	1606.4	3.80	36.62	21.19	4.7	45.30
1590	75.7	1585.2	3.88	36.90	21.47	4.6	43.75
1595	75.5	1589.4	3.92	37.38	21.95	4.7	44.82
1590	75.0	1600.0	3.84	36.86	21.43	4.6	44.16
1595	75.3	1593.6	3.80	36.33	20.90	4.8	45.89
1600	75.2	1595.7	3.90	37.34	21.91	4.8	45.95
1605	74.9	1602.1	3.78	36.33	20.90	4.7	45.18
2005	60.0	2000.0	3.70	44.4	28.97	4.0	48.0
1995	60.0	2000.0	3.90	46.8	31.37	4.0	48.0
1985	60.0	2000.0	3.80	45.6	30.17	4.0	48.0
2005	60.0	2000.0	3.60	43.2	27.77	4.0	48.0
1997	60.0	2000.0	3.85	46.2	30.77	4.0	48.0
2000	60.0	2000.0	3.80	45.6	30.17	4.0	48.0
2020	59.0	2033.9	3.70	45.1	29.67	4.0	48.8
2005	58.0	2069.0	3.60	44.6	29.17	4.0	49.6
2060	58.0	2069.0	3.75	46.5	31.07	4.0	49.6

LIST OF DATA FOR IGNITION SYSTEM

SPEED (RPM) DAYTRONIC	DISTRIB-UTOR CYCLE (MS) SCOPE	COMPUTED SPEED (RPM) FROM DIST	SPARK ADV BASED ON DIST (MS)	SPARK ADV BASED ON DIST (MS)	SPARK ADV ACTUAL (DEG CS)	DWELL (MS)	DWELL (DEG CS)
2370	50.4	2381.9	3.70	52.87	37.44	3.10	44.30
2350	51.0	2353.9	3.70	52.25	36.82	3.14	44.34
2340	51.1	2347.4	3.60	50.70	35.27	3.08	43.38
2345	51.7	2321.1	3.80	52.92	37.49	3.15	43.87
2330	51.6	2323.8	3.80	53.00	37.57	3.13	43.64
2350	51.1	2347.4	3.60	50.70	35.27	3.06	43.09
2360	51.1	2350.2	3.50	49.35	33.92	3.18	44.84
2335	51.2	2341.9	3.70	52.00	36.57	3.09	43.42
2350	51.3	2340.1	3.60	49.14	33.71	3.15	44.30
2840	41.0	2926.8	3.16	55.58	40.15	2.50	43.90
2845	42.0	2857.1	3.27	56.06	40.63	2.55	43.71
2850	42.0	2857.1	3.20	54.94	39.51	2.50	42.86
2845	42.0	2857.1	2.98	51.09	35.66	2.55	43.71
2845	42.0	2857.1	2.91	49.97	34.54	2.50	42.86
2830	41.0	2926.8	3.02	53.03	37.60	2.50	43.90
2870	40.0	3000.0	2.91	52.47	37.04	2.50	45.00
2865	41.0	2926.8	3.12	54.88	39.45	2.50	43.90
2900	40.0	3000.0	3.01	54.27	38.84	2.50	45.00

VITA

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DESIGN AND TESTING OF A MICROCOMPUTER AIR-FUEL RATIO, IGNITION TIMING SYSTEM, FOR AN ELECTRONICALLY FUEL INJECTED INTERNAL COMBUSTION ENGINE

by

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B.S., Kansas State University, 1975

AN ABSTRACT OF A THESIS

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ABSTRACT

In recent years, pollution has become a major societal problem and emission control has become a major concern of the automobile industry. With the advent of fuel shortages and rapidly rising fuel prices the automotive industry now faces the problem of maximizing fuel economy and continuing to decrease exhaust emission levels without sacrificing performance. The basic difficulty is that engine changes which increase fuel economy usually increase emission levels while reducing emission levels susally also reduces fuel economy.

Emission legislation will impose HC/CO/NOX limits of 1.5/15/2.0 gram per mile by 1977 and 0.41/3.43/1.0 grams per mile by 1981-82. Fuel economy legislation requires an average 18 miles per gallon by 1978 and 27.5 miles per gallon by 1985. In order to meet these goals extremely accurate control in metering and mixing the fuel and air also in firing time of engine is necessary.

The objective of this thesis was to control simultaneously spark timing and air fuel ratio by the microcomputer. The scope of this work was limited to testing engine speeds between 1000 and 3000 rpm and engine loads between 10 and 40 lb-ft. at 3 different air-fuel ratios of 14-1, 16-1, 18-1. The air-fuel ratio and spark time controller were open loop, nonfeedback control system, based on the computational approach.

Testing was performed on a 1968 model, 96.6 cubic inch displacement, four cylinder, horizontally opposed, air cooled spark ignition, internal combustion Volkswagen engine equipped with a Bosch injection system. Data for the air fuel ratio testing was collected, following an engine warm at combinations of three loads, 10, 25 and 40 lb-ft and three different speeds of 1200, 2000 and

2800 rpm and air fuel ratios of 14-1, 16-1, 18-1. For the ignition, spark advance and the ignition dwell testing, data was taken at six different speeds of 1000, 1200, 1600, 2000, 2300, 2800.

The result of testing the air-fuel ratio controller showed a percentage of offset exceeded 5% on seven of the 27 sets of data with average percent offset of 3.589%, while the percent standard deviation only exceeded 5% on one set. Results of the uncertainty for air-fuel ratio measurment showed limit of error of 3.3%. The ignition spark advance testing result was successful with the maximum deviation of 1.5 degrees of crank shaft. The average deviation for the six sets of data was less than 1.0 degree of crank shaft. Average percent standard deviation for these data was 3.67%.

Ignition dwell system showed better results with the maximum offset of 3.5 degrees crank shaft and an average error of 1.2 degrees of crank shaft. Uncertainty for this measurement showed between 1.24 and 3.08 degree crank shaft limit of error.