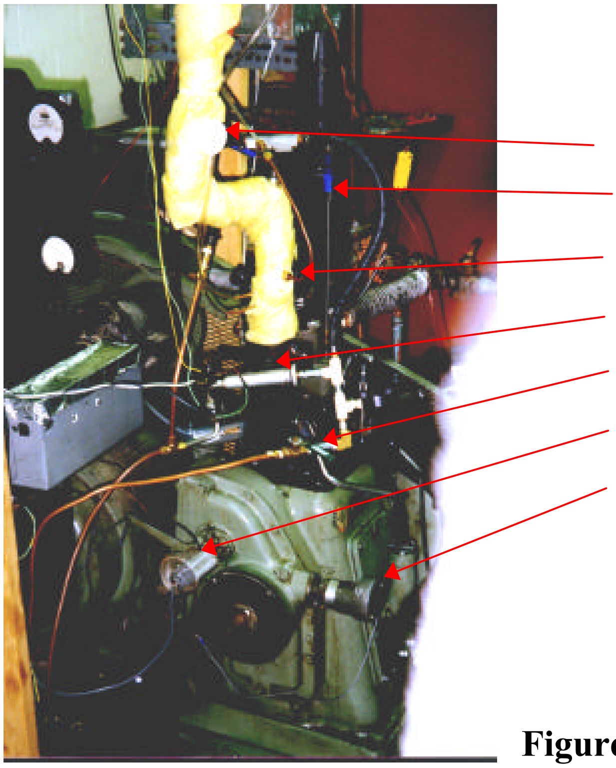
CHAPTER 2
Experimental Systems

2.1 Introduction

To study the effects of increased ignition energy on cold start hydrocarbon emissions, a test apparatus was designed and constructed. The test apparatus was designed to produce cold start condition similar to those encountered by an automobile. The key design criteria required that the test apparatus return the engine to the cold start conditions rapidly after each test run. Other criteria required a range of test conditions possibilities and the ability to adapt for future experiments. Cost was a controlling criterion also. To reduce cost, the test apparatus was created from a mix of available equipment and new equipment.

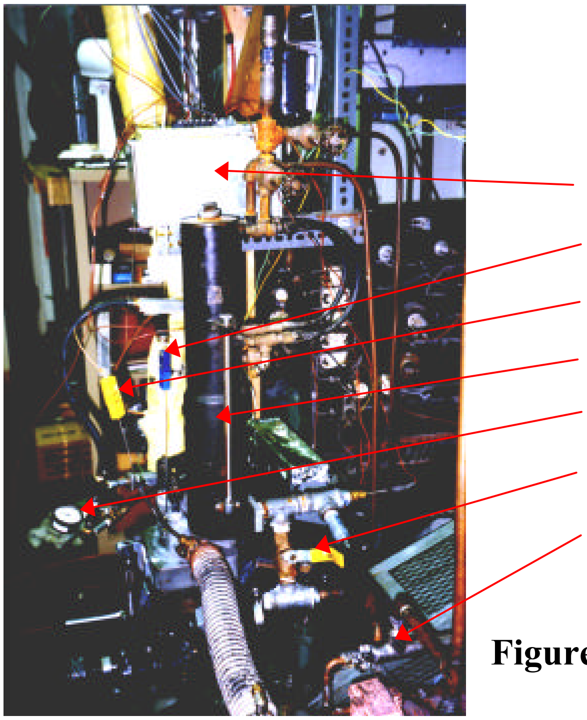
The test apparatus was designed around a single cylinder ASTM-CFR test engine. The test engine was modified as needed to support the experiment. Four major modifications were made to the engine and its systems. The changes involved the engine cooling system, ignition system, fuel system, and the air supply system. The cooling system controls the temperature of the engine and air. The ignition system consists of the stock CFR engine ignition system and a supplemental high energy unit. The fuel injection system is a port type developed for this test. Each modification is discussed with greater detail in a separate section following the introduction. A computer operating two data acquisition cards collected data on the emissions and temperatures of the engine for each test run.

Photographs of the setup are supplied in Figures 2.1 -2.4. Accompanying the photos are lists of the major components shown in each picture. Block drawings of the test apparatus are also supplied in the detailed description sections.



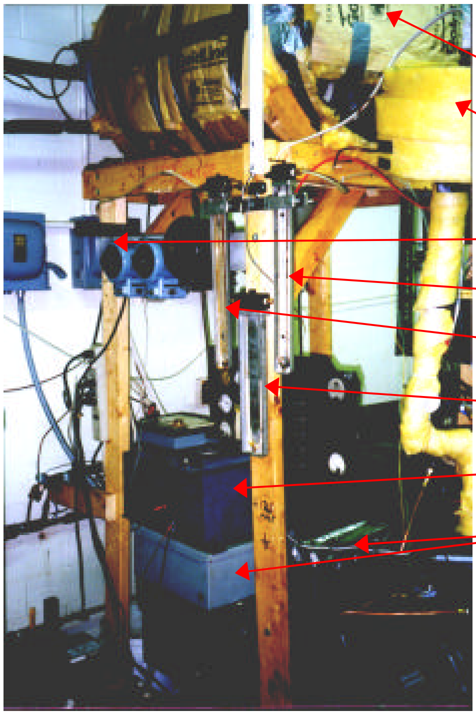
1.) Auxiliary Air Outlet
2.) Cylinder Temperature Probe
3.) 2nd Pressure Tap
4.) Fuel injector
5.) Fuel Pressure Control valve
6.) Fuel Injector Infrared Trigger
7.) Ignition Points

Figure 2.1 Picture #1 Of Apparatus



9.) Thermocouple Ice Bath Reference
10.) Cylinder Temperature Probe
11.) Exhaust Temperature Probe
12.) Water Cooling Tower
13.) Fuel Pressure Gage
14.) Coolant Flow Bypass Valve
15.) Water to R-22 Heat Exchanger

Figure 2.2 Picture #2 Of Apparatus



16.) Pleneum and Cold Air Reservoir

17.) Intake Air Heater

21.) Air Heater Control VARIAC

18.) Manometer for Pressure Tap #2

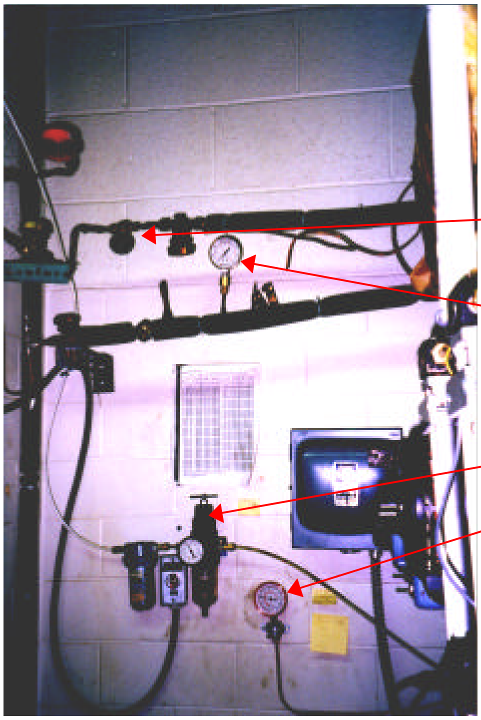
19.) Manometer for Exhaust Pressure Tap

20.) Manometer for Pressure Tap #1

22.) High Energy Ignition Power Supply

23.) High Energy Ignition Circuit

Figure 2.3 Picture #3 Of Apparatus



24.) R-22 Manual Flow Control Valve for Cold Air Supply

26.) A/C Suction Line Pressure Gage (Air Cooling system)

25.) Hot Gas Bypass Control

27.) A/C Suction Line Pressure Gage (Water Cooling System)

Figure 2.4 Picture #4 Of Apparatus

2.2 Test Apparatus

2.2.1 Test Engine

The engine used to run the test was an ASTM-CRF Fuel Testing Engine made by Waukesha. The engine was originally designed in 1930. This particular engine was made in 1948. The engine was designed to function as the standard engine by which the knock characteristics of motor fuels could be measured. As with most standardizing test equipment the overall design of the engine has not changed with time. Technological advances in ignition systems and fuel delivery have found there way on to their newer models. These advances come in the form of fuel injection and breakerless ignition over the carburetor and conventional point ignition systems used on the 1948 model.

The CFR test engine is a single cylinder engine. It has a bore of 82.55mm. and a stroke of 114.3 mm giving it an overall displacement of 0.612 liters. The compression ratio can be varied from 5:1 to 10.5:1. Throughout the experiment compression ratio was set at 9:1. The engine can be operated at 600, 900, and 1200 rpm. For the experiment the engine was operated at 900 rpm . The speed is controlled by a small dynamometer. The fuel mixture enters and leaves the cylinder through the flat cylinder head design. The design of the cylinder head is old-fashion by today's designs. The cylinder head has two overhead valves. This design has not changed on CFR engines through the years. The engine can be outfitted with shrouded valves but was not for this experiment. Because of the engine's original intended test purpose, it is very robust and versatile. This has led to its use by many in researching internal combustion engine operation and emissions. To conduct Cold Start Emissions Testing, three of the engine's main systems were modified. The modified systems were the ignition system, the mixture preparation system and the cooling system.

2.3 Engine Modifications

2.3.1 Engine Cooling

The EPA's cold start emissions test calls for a car to soak overnight in temperatures around 20° C after conditioning. This time period allows all the components in the car's engine to reach the equilibrium temperature of around 20° C also. In an experimental setting were several successive runs are needed, it is not feasible to wait 12-24 hours for the engine to cool between runs. A cooling system was designed and implemented to allowed the engine to be cooled down to test conditions within an hour after each run. The test conditions can be found in Chapter 3. The cool down system connects to the stock cooling system to allow the engine to function as originally designed when not being forced cooled.

The stock engine coolant system consist of a water reservoir that circulates water through natural convection. The cool water held in the reservoir enters the block around the base of the cylinder sleeve. The heat transferred from the combustion process heats the water in the jacket. As the water is heated, natural convection forces it to circulate through the water jacket in the cylinder head than the back to the reservoir. Because the system is not pressurized, as is the case with car cooling systems, the top of the reservoir has two steam condensing coils that prevent all the water from being boiled out. The coils condense the steam, and it drips back in to the reservoir. Tap water runs through the coils to keep them cool.

The flow of the engine's cooling water was modified to increase the cooling capacity and facilitate rapid cooling of the engine (Figure 2.1). The water's path exiting the reservoir on route to the engine was altered to allow it to flow through a tube-in-tube heat exchanger. After the heat exchanger, the water is routed back to base of the cylinder's sleeve. A pump was added to force the cold water through the heat exchanger and the cylinder when needed. Because the pump was one speed a valve was added after the pump to control the flow if needed. A bypass route with cut off valve was also placed in the cooling system. This bypass allowed the water to flow in stock

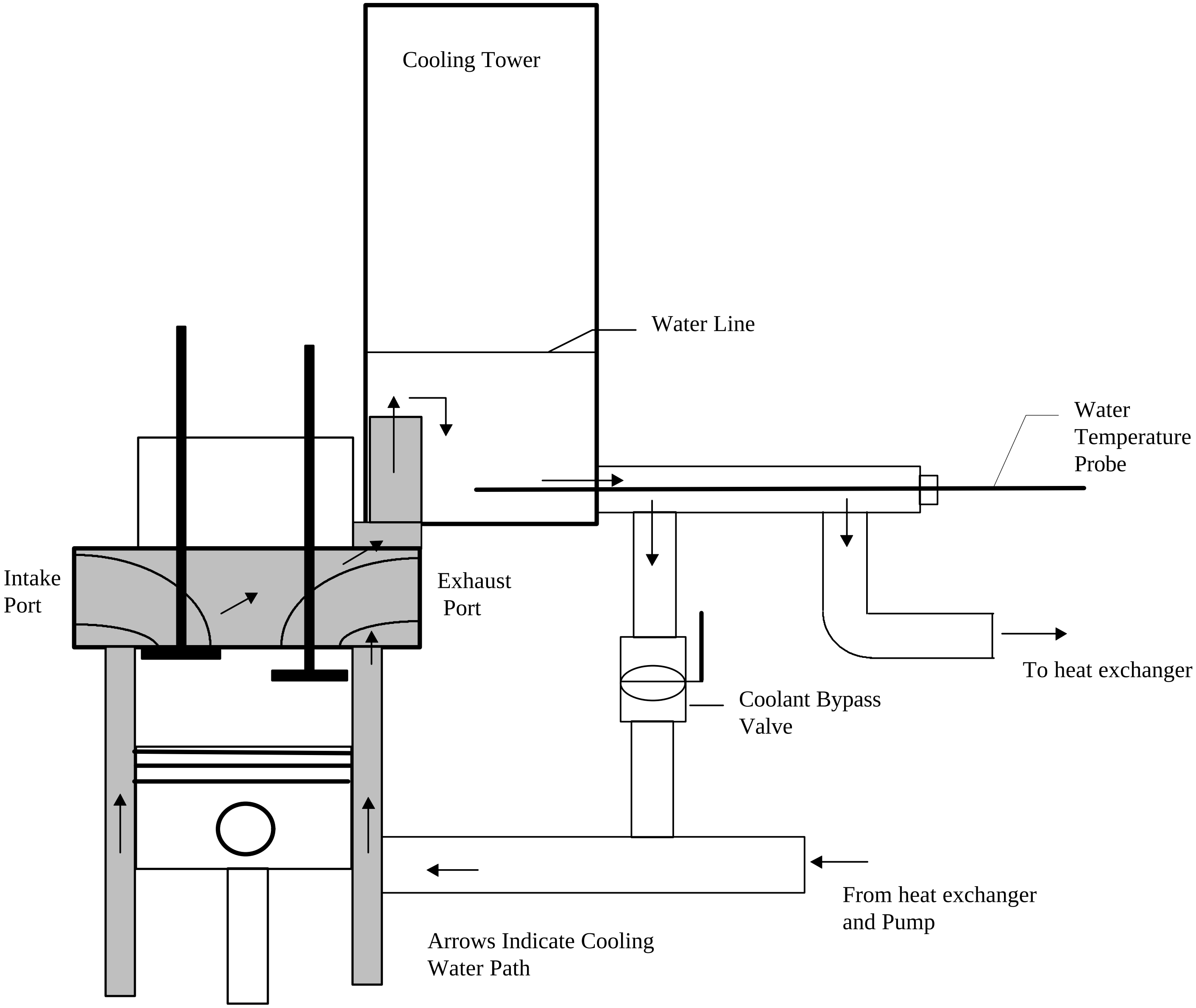


Figure 2.5 Water Cooling Circuit Diagram

configuration with out going through the heat exchanger. This kept engine's original cooling system intact.

The heat exchanger has refrigerant 22 in the inner tube and water flowing the annulus. The refrigerant is supplied by a 10 ton condensing unit, of which only about 3 tons are needed. The system is capable of cooling the engine from 120° C to 0° C in 45 minutes. The cooling system can be used to significantly slow the rate at which the engine rises to operating temperature or maintain a steady operating temperatures in the cylinder head of 55° C- 65° C.

2.3.2 Air Supply System

Fuel vaporization problems in cold start conditions are a major contributor to cold start hydrocarbon emissions. For this reason, it was important to be able to supply the intake air charge at the temperatures cold enough to model cold start conditions even in the middle of summer. The intake air conditioning system, designed to handle this task, can cool room air to temperatures as low as 0° C or heat it up as high as 110° C (Figure 2.2)

Room air is pushed though a series of finned heat exchangers by an external fan. The heat exchangers are supplied with refrigerant 22 from the 10 ton condensing unit. The cool air is then stored in a 50 gallon plastic drum which functions as a cold air reservoir and pleneum to dampen out pulsation. The temperature of the air is controlled by the refrigerant flow through the heat exchanger. The flow was originally controlled by a 1/2 ton expansion valve. The TX valve was later changed over to a manual valve because the refrigerant flow necessary was so low the 1/2 ton valve would not open. Cold air stored in the drum is then drawn past an air heater by the engine (Figure 2.2). The air heater can increase air temperature a maximum of 100° C. The temperature of the heater is regulated by a variable AC voltage controller. The fan was added to enable the reservoir to be filled with cold air without motoring the engine. An auxiliary air output was placed down stream of the air heater. This output, when open, enables the fan to circulate cold air from the reservoir through the intake piping. The circulating of air allowed the final air temperature entering the engine to be set and kept constant before the test runs starts. When the engine is turned on the auxiliary output is closed off and the air is routed to the engine.

There are two pressure taps in the intake system. They allow the intake vacuum to be measured. Both are connected to U-tube manometers with H_2O for the fluid. By measuring the pressure drop between the two pressure taps the air flow can be estimated.

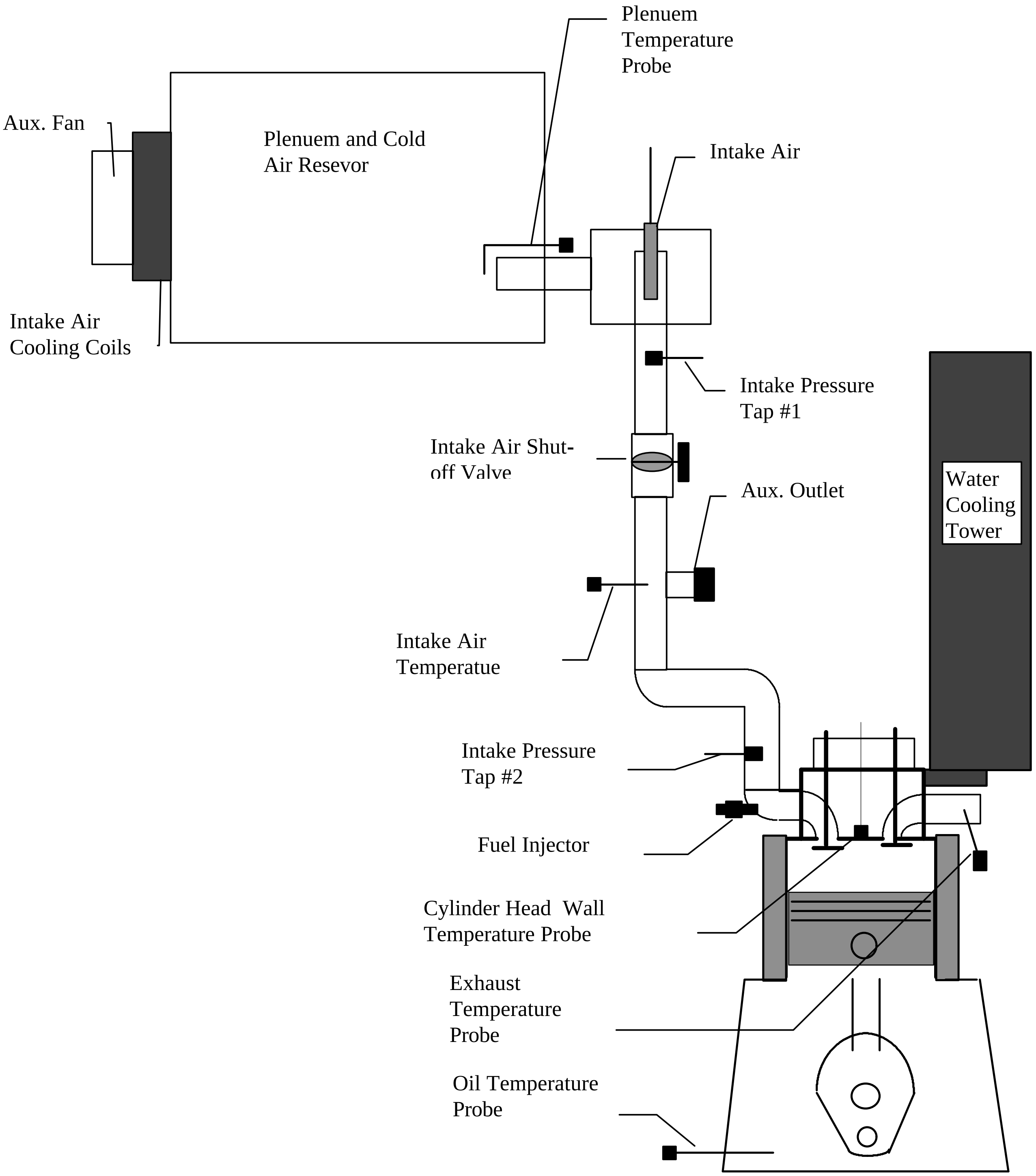


Figure 2.6 - Air Conditioning and Supply Diagram

2.3.3 Ignition System

The Waukusa CFR engine used in the experiment came equipped with a variation of the conventional point type ignition system. The stock ignition system was retained for the experiment, however a supplemental variable high energy ignition system was added in conjunction to meet the need of the testing. Similar to the conventional point system found on automobiles, the CFR engines has an ignition coil, a point contact (point) activated by ignition timing cam, and a spark plug. Since the CFR is a single cylinder engine there is no distributor and only one timing event is designed into the timing cam. Although the parts are the same, the method in which they provide ignition energy is fundamentally different. The difference between the point ignition system on the CFR and the style on conventional automobile revolve around how the energy for the ignition sequence is stored and released each time the timing cam opens and closes the points.

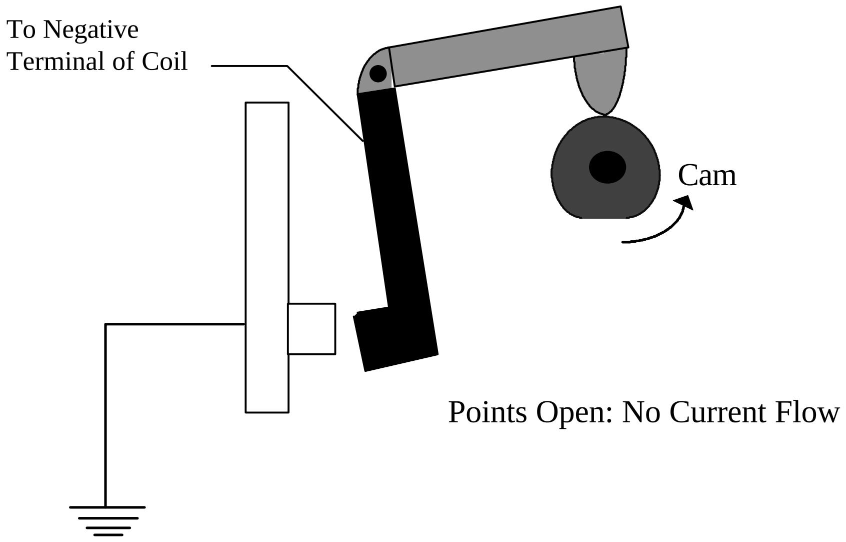
In conventional systems the points are closed between firing. While the points are closed a low DC voltage is supplied to the coil, the current flow through the low voltage windings of the coil induces a strong magnetic field. When the points open, the positive current flow through the low voltage windings stops. The magnetic field around the coil that was created by the current flow breaks down. The break down of the magnetic field creates a current spike and flow in the reverse direction. The negative current spike in the high voltage windings of the coil cause an arc across the spark plug gap. The low voltage windings also experience a current spike. The current spike in the low voltage winding is absorbed by the condenser inside the distributor[24].

The points ignition system on the CFR engine works in reverse of the conventional system. It uses the sudden build up of the strong magnetic field around the coil to create the current spike needed to fire the spark plug. It functions more along the lines of a step-up transformer than an energy storage device as with conventional point systems. On the CFR engine, the low voltage winding is supplied by a variable voltage source. It can be set for an input voltage of 0 to 130 VDC. For the test duration of the experiment it was set at 130 VDC, which is around one order of magnitude higher than the voltage supplied to the low voltage windings on most automobile ignition systems. The supplied voltage level is controlled by a rheostat on the engine's control panel, and it is equipped with a voltmeter to show the voltage setting.

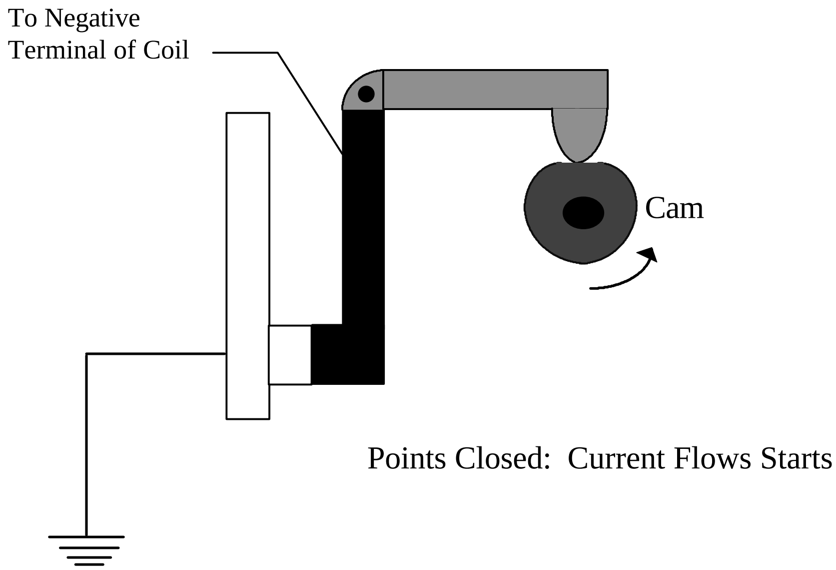
The ignition timing cam turns at half the speed of the crankshaft. It is perfectly round for 300 degrees. Then there is a flat face that makes up the other 60 degrees of the cam. The points linkage rides on the cam face. When it is riding along the round portion of the cam the point contact is open. The 60 degree flat face closes the point contact and cause the system to fire (Figure 2.3). Unlike the conventional system that charges the coil when the points are closed and fires when the points open, the CFR engine's ignition system fire when the points close. When the points close on the CFR system, a current spike from the 130 VDC source flows through the low voltage windings, primary windings. The current spike creates a sudden strong magnetic field which cause current spike in the high voltage windings. The current spike arcs across the spark plug gap. The spike of positive potential in the low voltage side induces a spike of positive potential in the high voltage winding. The positive spike is opposite of that created in most automotive style point ignition systems.

The high energy part of the ignition system was designed by Ralf Ochel [23]. It was loosely based on the ignition system used by Asik[21] and Topham[22]. The schematic of the ignition systems final design are shown in Figure 2.4. A more detailed schematic of the power supply for the portion supplying the high energy to the system and the spark gap are shown in Figure 2.5 and 2.6, respectively. Ralf Ochel used the system to study the effects of increased ignition energy and plasma jet ignitors on NOx reduction for natural gas engines.

The high energy ignition system is capable of providing up to 2 joules of energy in addition to that provided by the CFR's conventional (low energy) ignition system. The capacitor used to store ignition energy was a 2500 VDC 1 μF. The power supply shown in Figure 2.5 charges this capacitor to full capacity (2200 Volts) within 2 crank revolutions. The calculations confirming this are provided in the APPENDIX B and were checked by monitoring the capacitor's charge with the oscilloscope. The timing of the capacitor discharge is controlled by the low energy ignition system. The low energy system initiates the ignition process when its high voltage current arcs across the spark plug gap.



Points Open: No Current Flow



Points Closed: Current Flows Starts

Figure 2.7 - Ignition Point Operation Diagram

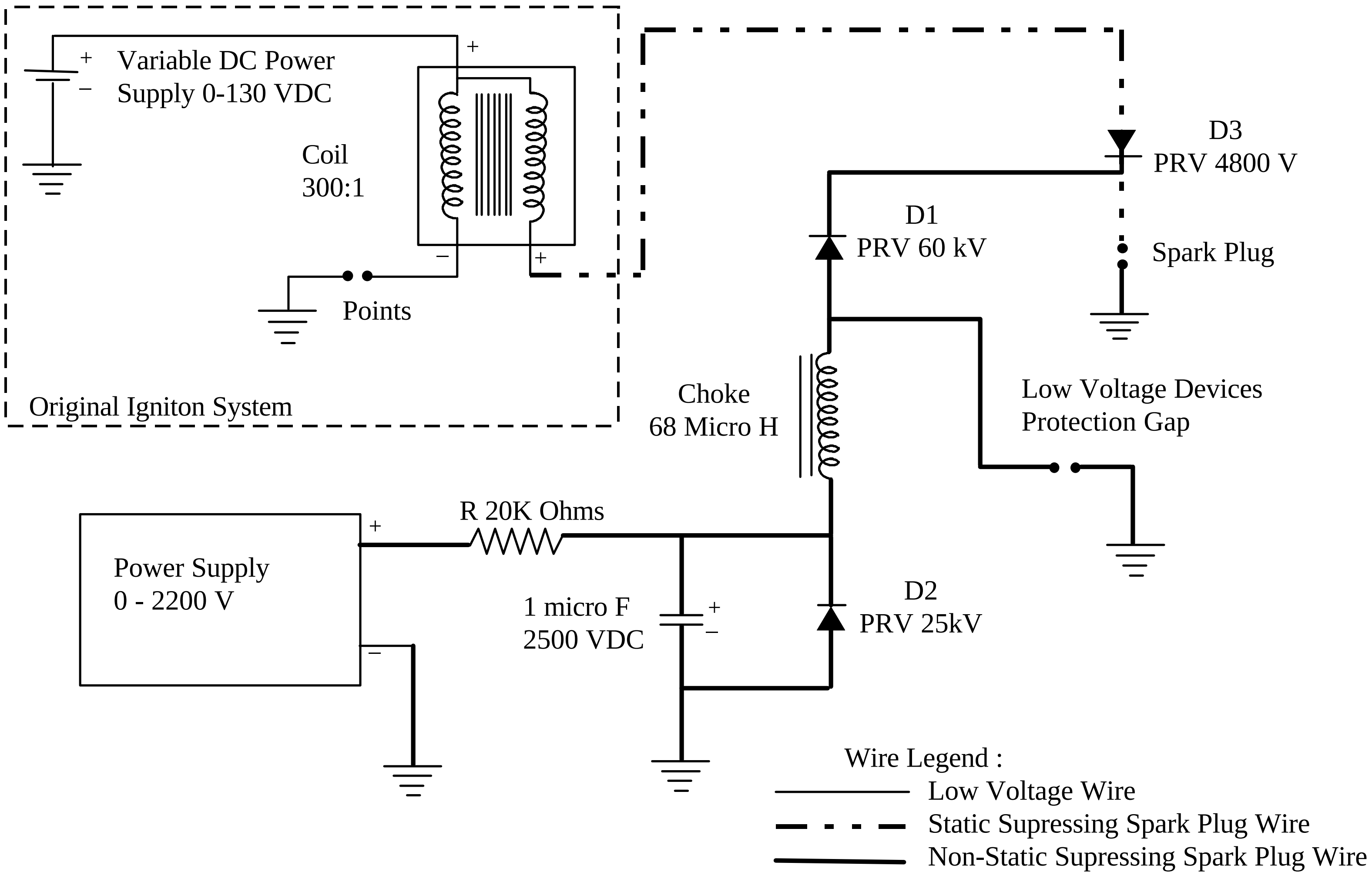


Figure 2.8 High Energy Ignition System

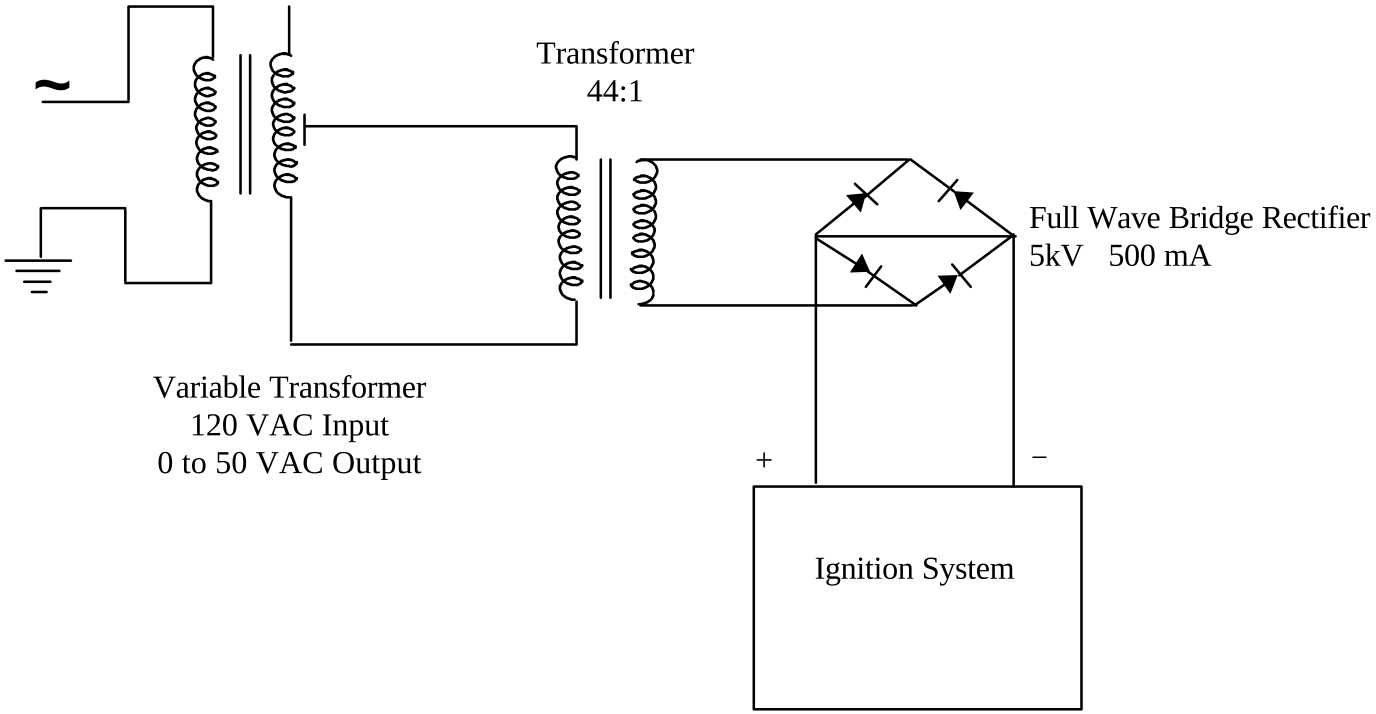


Figure 2.9 - High Energy Power Supply

Once the low energy system starts the breakdown process across the gap of the spark plug, the high energy ignition system's capacitor can discharge up to 2 joules of energy through the spark plug. To prevent the low energy system from discharging through the high energy system two, 30 KV peak reverse voltage diodes were placed in series on the high energy systems output. To protect the diodes from output currents exceeding 250 amps, a 68 μH choke was used. To prevent the high energy system from discharging through the low energy system's ignition coil, a string of 400V peak reverse voltage diodes were placed in series. Twelve diodes were used to create a one diode with an effective peak reverse voltage of 4800 volts.

The high energy ignition (HEI) system was a large source of electro magnetic interference. When the HEI system was reconstructed following Ochel's [23] design, it was capable of creating enough interference to lock up the computer being used for data acquisition. It was found that some of the spark plug wires used throughout the ignition had cracks. Following Ochel guidelines on placement, new static suppressing and non-static suppressing spark plug wires were used. The location and type of wire used are shown in Figure 2.4. The new wires lowered the level of noise enough that the computer would not lock up. There was still enough interference being given off to make the thermocouple signal extremely noisy.

In the original setup, the D/A terminal board was approximately 6 ft from points were the temperature was measured. The initial setup had the unshielded thermocouple wire running the full six feet to a ice bath reference junction then the D/A terminal board. This setup was changed and the ice bath moved to a central location above the engine. Moving the cold junction closer to the location of the temperature measurements allowed shorter unshielded leads to be used. This location allowed for the shortest possible leads on all 8 thermocouples. From the cold junction double shielded computer cable carried the compensated signal to the terminal board. At the terminal board all eight channels were passively filtered of high frequencies for added protection against noise. The low pass filter was formed using the combination of a 4.7 μF capacitor and a 10000 ohm resistor. The combination of the filter and the shielded wire cured the noise problem.

2.3.4 Electronic Fuel Injection

In its original form the CFR engine used a carburetor to meter its fuel supply. For this experiment, a computer controlled single fuel injector replaced the carburetor. The carburetor, although it still functioned, was not capable of supplying enough fuel to start the engine when cold. The carburetor also lacked the ability to control the rate at which the cold start enrichment was reduced as the engine temperature increased. The addition of the fuel injector allowed the A/F ratio to be changed versus time and engine conditions.

The mechanical parts of the EFI system included a single fuel injector, fuel pump and gas tank from a 1996 Chevy Lumina. A ball valve on the return side of the injector controlled fuel pressure. The pressure was set at 50 psig and left through out the duration of the experiment. The control side of the EFI system consisted of a infrared trigger and its signal processing circuit Figure 2.10, a 486 computer with D/A card, and fuel injector driver circuit Figure 2.11. The control theory for the setting the injectors pulse width was kept simple because of the nature of the test and the engine's operation.

The engine operates with a unrestricted air flow and at a constant RPM. By controlling the air temperature and moisture, the mass flow of air into the engine is kept constant. Using the manometers an estimate of this flow rate was calculated. Knowing that the air flow was constant over the duration of the test, no provision had to be made in the control routine for measuring mass air flow. This assumption proved not to be accurate. It is further discussed in Section 4.2.2. Production EFI systems are also capable of correcting the injectors pulsewidth for varying engine component temperatures like coolant and block temperature. This provision was also not needed because the variation of temperatures versus time for the warm up phase between different cold start runs was negligible. With this being the case, the length of the pulsewidths opening and closing the fuel injectors were programmed to change with time by counting the number of engine cycles with the computer.

The timing of the injector firing is controlled by the infrared trigger. The trigger consist of a IR phototransistor, IR emitting diode, and timing wheel. The timing wheel spins at half engine speed and is mounted to the unused second timing cam for the ignition points. The wheel has a slit that allows IR light to hit the phototransistor for a split second. When the phototransistor senses the IR light, it energizes allowing current to flow to a transistor. The transistor amplifies the voltage. The transistor’s on/off voltage signal is processed through an op-amp into an inverse square wave that is capable of triggering the computer through the D/A board. The computer, once triggered, calculates the pulsewidth needed to supply the correct amount of fuel. The calculation is based on number of firing cycles the engine has experienced.

The computer does not make a square pulse used to drive the fuel injector, but through the two digital to analog output channels creates a sawtooth wave form and a reference voltage signal. D/A channel 0 produces the sawtooth wave and D/A channel 1 produces the reference voltage. These two voltages are sent to an op-amp. The op-amp acts as a comparator. When the voltage of sawtooth wave is greater than the reference voltage the op-amp sends +18 volts to the power transistor. If the sawtooth voltage is less than the reference voltage the op-amp sends a -18 volts to the transistor. By controlling how long the voltage of the sawtooth wave is greater than the reference voltage, a square wave of calculated duration is formed through the op-amp. It is a simple form of pulsewidth modulation. The ± power voltage supplied to the op-amp producing the square wave has significant effects on the ability of the transistor to fire the injector. This voltage has to be kept constant if the pulsewidth is to be accurate. If the voltage fall to the point were the current is not high enough to rapidly activate the injectors, then less fuel will be supplied than calculated. The op-amp does not directly drive the injector. It can not handle the current required to drive the fuel injector, its output is sent to a high power transistor. The transistor is supplied with +20 volts to its collector and functions as a current amplifier. It amplifies the current being supplied at the voltage seen across its base and emitter. The voltage at the op-amp must be kept high enough to provide a signal strong enough to be amplified by the power transistor. The FORTRAN program used and the pulsewidth versus A/F ratio plot for are supplied in the Appendix B. The pulsewidth vrsus A/F ratio calibration holds only for conditions given with plot. Changes in conditions require recalibration.

The fuel used for all test runs was provided by the Virginia Tech Motor Pool. The fuel was purchased through Webb Oil Company in Roanoke Va. It was summer grade 87 octane un-oxygenated gasoline.

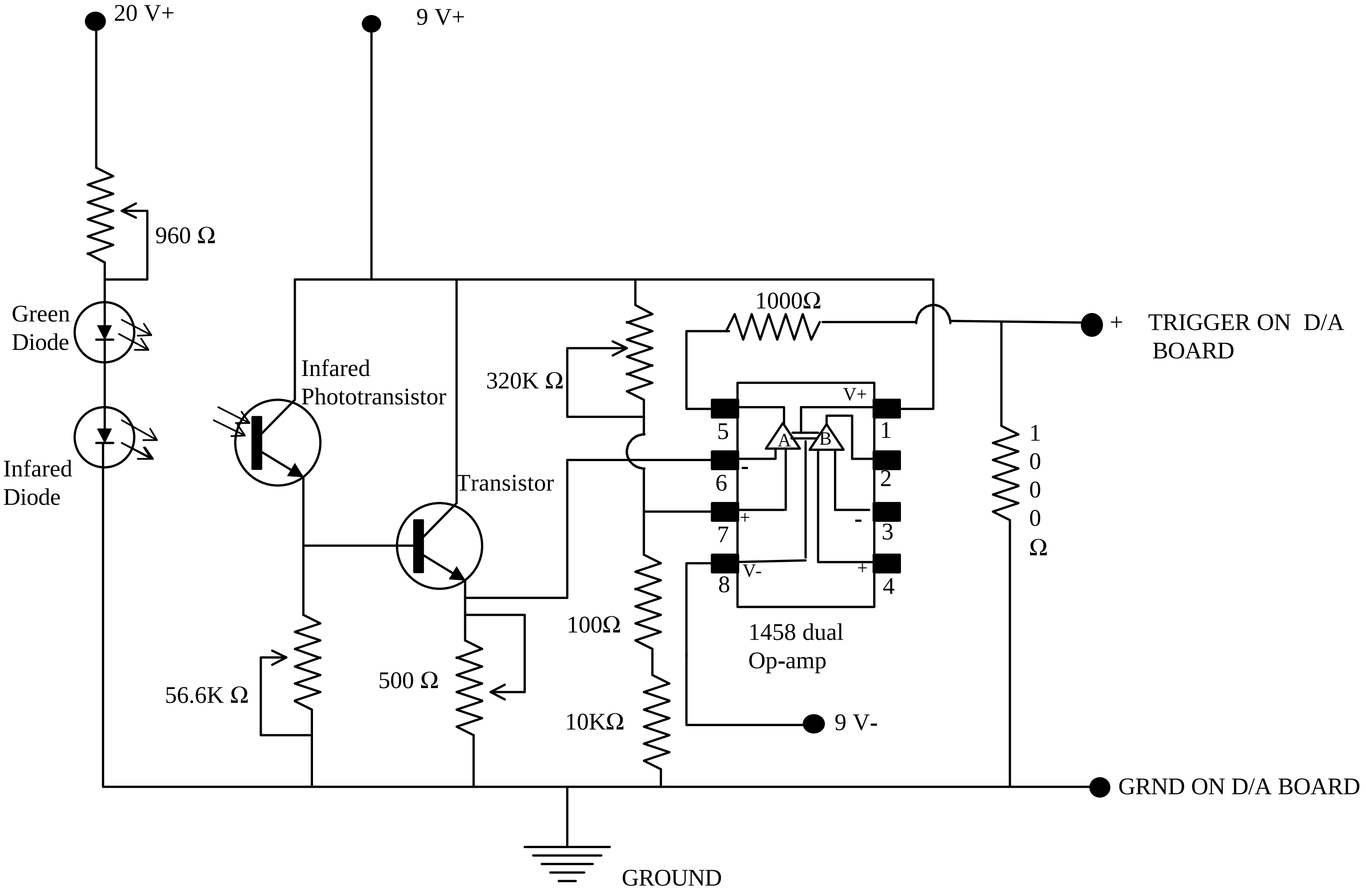


Figure 2.10 - Fuel Injector Trigger Circuit

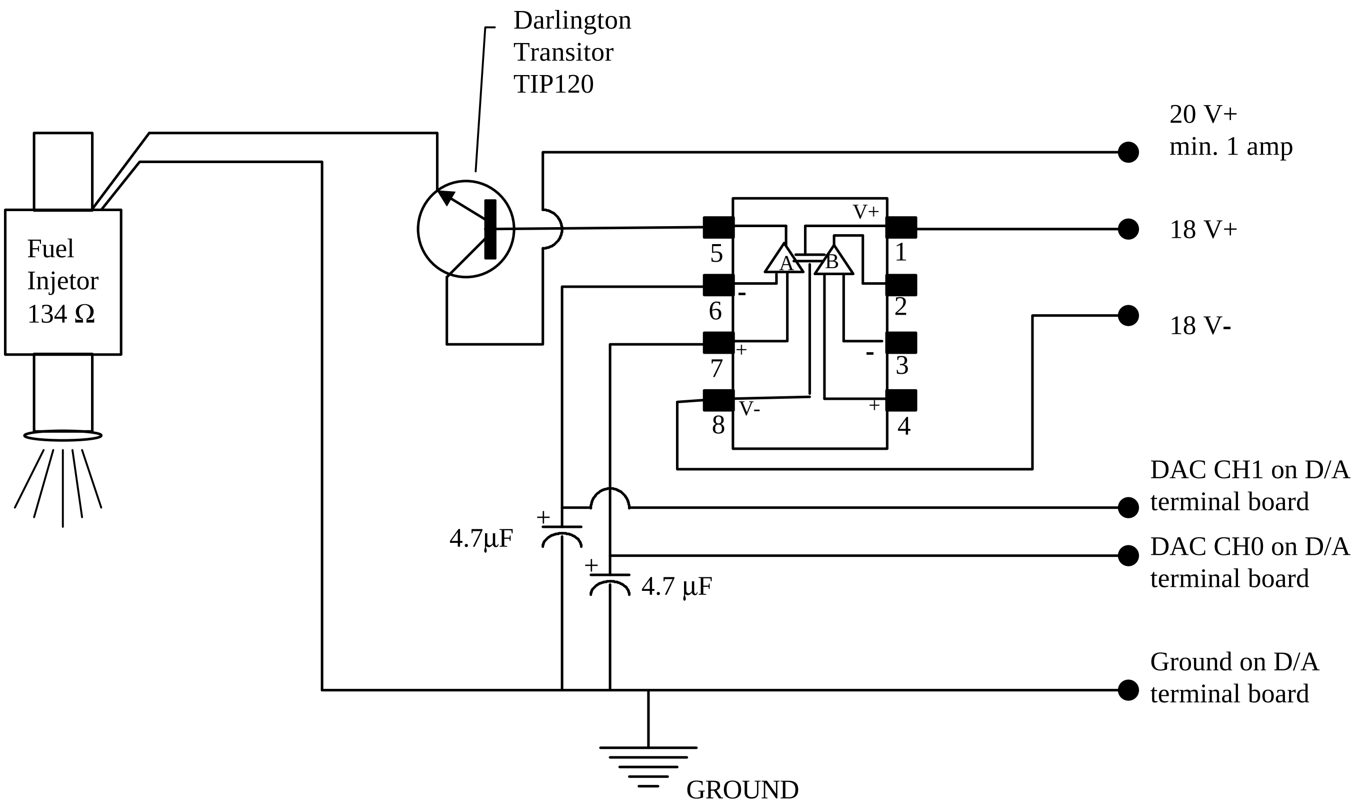


Figure 2.11 - Fuel Injector Driver Circuit

2.4 Temperature Measurements

To correlate the engine's emissions with engine temperatures, the CFR engine was outfitted with 5 thermocouples. The thermocouples allowed the measurement of what was considered to be the most important engine temperatures effecting cold start emissions. The temperatures measured for the experiment were cold air reservoir, intake air, The cylinder wall, coolant temperature, oil temperature and exhaust gas temperature.

All temperatures except exhaust temperature were measured with a type T thermocouples. The exhaust temperature was measured by a type K thermocouple. The thermocouples where referenced by common ice bath. Due to availability, unshielded thermocouple wire was used. The unshielded thermocouple leads turned out to be highly susceptible to the RF noise being produced by the high energy ignition system. To reduce noise interference, the ice bath was moved to a position that allowed the shortest length of unshielded thermal couple wire. From the reference junction to the Data Translation DT707-T screw terminal, double shielded wire was used. The reference junctions for the thermocouples were copper-copper and constantan-copper for the type T thermocouple. The Type K reference junction consisted of and chromel-copper and constantan-copper. The union of these wires were covered with clear RTV silicon and placed in the ice bath.

Starting with room air and following its path through the test apparatus the placement of the thermal couple probes are displayed in Figure 2.2 and 2.6. The first probe is centered at the exit of the cold air reservoir. The exit passage leads to the intake air heater. The reservoir probe measures the temperature of the cold air stored in the 50 gallon pleneum. The second probe is placed 21-1/2 inches down stream of the air heater. The thermocouple bead sits on the centerline of the 1-1/4 in nominal schedule 40 PVC pipe. The pipe is the intake passage.

The CFR engine was designed to test a fuel knock characteristics. Because of this intent, as provision was made in the top of the cylinder head for a knock sensor. This sensor was not used for the experiments, instead the threaded boss was fitted with a plug. The plug was machined to accept a thermocouple probe. The boss was machined to allow the probe's tip to sit 0.010 inches from the inner surface of the cylinder head (figure 2.8) while remaining protected inside the plug.

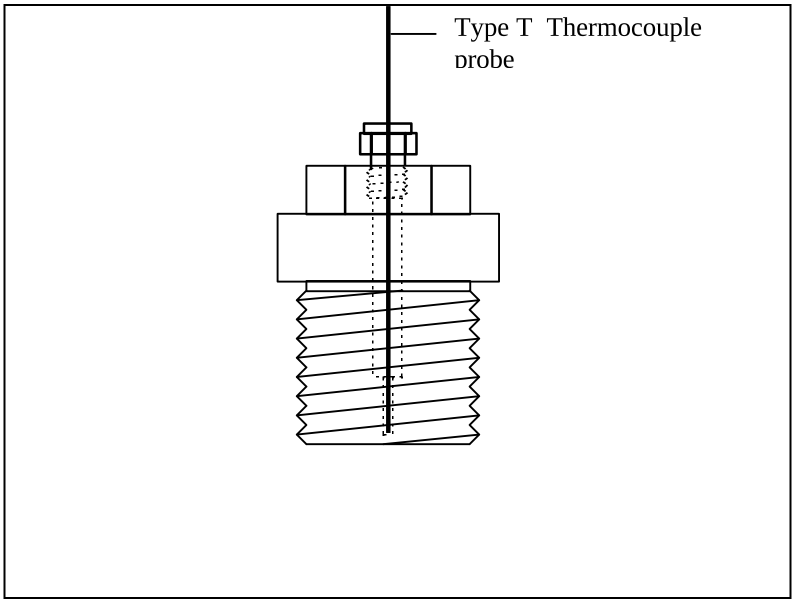


Figure 2.12 - Cylinder Head Temperature Plug.

The exhaust temperature is measured in the exhaust manifold about 2.5 inches down stream of the exhaust valve. A type K thermocouple probe was placed on the centerline of the exhaust manifold. The final temperature measured on the engine was water temperature. The placement of the probe is illustrated in Figure 2.1

The acquisition of all temperature measurements was handled by a Data Translation DT-2811 PGL D/A board. The DT-2811 data acquisition board is a high gain board capable of reading unamplified thermocouple signals. It was used in 8 bi-polar channel mode. The boards gain was set to its maximum setting 500, which allowed the highest resolution. As mentioned in the section on the ignition system, a passive low pass filter processed the signal to rid it of unwanted background noise. Each temperature was monitored and saved on a one second interval. LABTEC software controlled the boards and stored the data to the appropriate files.

2.5 Exhaust Gas Analyzers

2.5.1 OTC 5 gas analyzer

An OTC 5 Gas Monitor was used to handle composition analysis of the exhaust gases. The monitor is comprised of two systems. The first is the mini computer, the Enhanced Monitor 4000. The second is the 5 gas analyzer. The gas analyzer houses all the hardware needed to detect the amounts of O_2, CO, CO_2, NO_x, and HC (hexane). The Enhanced monitor 4000 mini computer operates the gas analyzer and collects all data and error codes. The computer operates off a scroll through menu. The important functions used during testing were data sampling and storage, calibration, zeroing, air/fuel ratio, print option, and the ability to self test for bad sensors.

The 5 gas analyzer was designed to be used in an automobile's tailpipe. For this reason it has its own sample pump and three stage filter. It also comes with its own source of calibration gas. The calibration gas has known concentrations of CO, CO_2, NO_x, and hydrocarbon gases (propane). The concentrations of the fore mentioned gases in the bottle are 1.01 % CO, 5.99% CO_2, 996 ppm NO_x, and 297 ppm propane.

The concentrations of CO, CO_2, and hexane are determined through the infrared light absorption method. When a beam of light is passed through a gas, a certain amount of the light is absorbed at any given wavelength. This amount is proportional to the concentration of the gas. CO, CO_2, and hexane all absorb light in the infrared spectrum. Given the concentration of gas is fixed, the amount of light absorbed becomes a function of wavelength. The wavelength at which maximum absorption occurs is the gas's absorption maximum. CO has two maxima at 4.62μm and 4.70 μm. CO_2 has absolution maxima at 4.25μm and between 2.6μm and 2.8μm, and hexane has it maximum light absorption at about 3.4 μm wavelength. Using the principle that each of the different gas have absorption maxima at different frequencies of light, the concentration of each gas can be measured directly by measuring the amount of light absorbed only at theses unique frequencies.

The gas analyzer uses a resistive element heated piece of ceramic to emit the infrared energy. The temperature of the ceramic is precisely controlled to ensure even emission over the infrared frequency band. The IR light passes through the sample cell and is measured by three separate detectors. Each individual detector has a narrow band filter to pass only the frequencies corresponding to the maxima of the exhaust gas it is responsible for measuring. The detectors create an analog signal which is converted to digital and read by the mini computer and displayed or saved to memory.

The O_2 sensor and NO_x sensor measure oxygen and NO_x concentrations respectively through a chemical reaction. The type of chemicals used in the cell could not be obtained from the manufacturer. However, the sensors chemically react to its specific exhaust gas component's concentration producing a current proportional its concentration. The current is measured and converted to a concentration.

2.5.2 Hydrocarbon analyzer

Hydrocarbon emissions form an automobile are made up many types of hydrocarbons. The percentage make-up of the exhaust HC is close to the percentage make-up as the fuel being burned. While the OTC gas analyzer uses of IR absorption to detect hexane concentrations, it neglects the other hydrocarbons formed during the combustion process. Because of this the actual overall concentration of HC's in the exhaust is higher than the concentration of hexane would dictate. For this reason a Rosemount Model 400A Hydrocarbon Analyzer was also used to measure total HC emissions for comparison to the OTC analyzer.

The Rosemount Model 400A is a flame ionization detection (FID) hydrocarbon analyzer. The analyzer passes a fraction of the exhaust sample though a small burner. Inside the burner the hydrocarbons in the exhaust sample that were not completely burned during combustion are burned to completion. The FID analyzer uses a small flame fueled by 40% hydrogen and 60% nitrogen to burn the exhaust hydrocarbons. By burning the leftover hydrocarbons with the hydrogen flame, positive ions and electrons are formed. These amount of positive ions and electrons is proportional to the amount of carbon being burned. By accurately metering the exhaust flow into the ionizing flame the actual amount of carbon can be detected.

During cold starts fuel enrichment can get as high as 1:1 A/F in order to produce enough gas vapor to ignite. Of this extremely rich starting mixture most of it will find its way out of the exhaust valve. The high levels of HC's produced during cold start were out of the operating range of the Rosemount Analyzer. However, the levels produced at a steady operating condition were within the operating range of the FID analyzer. A comparison of the Rosemount (FID) versus the OTC (IR of hexane) at steady state and for varying A/F is provided in Appendix D.

The Rosemount HC analyzer was calibrated to read 75% of the 1000 ppm range while being supplied with a sample gas containing CH_4 at 10300 ppm. The 10300 ppm of CH_4 is equal to about 1247 ppm for gasoline with a molecular formula of $C_{8.26}H_{15.5}$. A calibration curve and equation are provided in Appendix D.

2.5.3 Exhaust Gas Flow to Analyzers

Two flow paths were used for this experiment. The first was used for collecting the data on transient engine emissions. When collecting the transient data the OTC 5 gas analyzer was the only analyzer used. The second sample path was used when the HC reading from the OTC analyzer was compared to that of the FID analyzer. The two flow diagram illustrating the paths of the exhaust gas to the gas analyzers are provided in Figure 2.13 and 2.14.

The first path went from the exhaust tap through the sample chiller and to the sample line for the OTC 5-gas analyzer. In this configuration the sample pump was not used. The OTC had its own sample pump and required its sample to be close to atmospheric pressure. High pressure levels upstream of the OTC gas analyzer's sample pump caused the analyzer to display a error message. The only pressure provided was that from the engines exhaust. This pressure was around 8 inches of water at the exhaust tap. The OTC analyzer is outfitted with a 3 stage filter to prevent internal damage. The 5 analyzers inside the OTC unit receive their sample from the same inlet port. However due to slight variation in internal routing of the sample the individual analyzer show small differences in delay times. CO, CO_2, HC concentrations are measured by the same IR unit. The are the first to receive a portion the exhaust sample. The O_2 sensor receives its sample 2 seconds behind the IR sensors. The NOx sensor is 4 seconds behind the IR sensor.

The second exhaust path was used during the comparison test between the two analyzers (Figure 2.14). This path required the use of an external sample pump. The exhaust sample was drawn through the chiller by the pump. On the outlet side of the pump, sample pressure going into the Rosemount HC analyzer was set to 15 psig. The Rosemount HC (FID) analyzer requires a minimum sample pressure of 5 psig. To accommodate the OTC gas analyzer when the external sample pump was used a bubbler was made and placed in parallel configuration with the OTC sample line input. To control the flow to the bubbler and OTC analyzer, a valve placed in the line. The valve was then opened just enough to allow bubbles to form in the beaker. The outlet for the exhaust gas sample into the bubbler was about 1 inch below the water line. The formation of bubbles at a slow rate required the pressure to be slightly greater than 1 inch of water above atmosphere. Because the gases are toxic the sample flowing through the bubbler was collected and vented with the other exhaust gases.

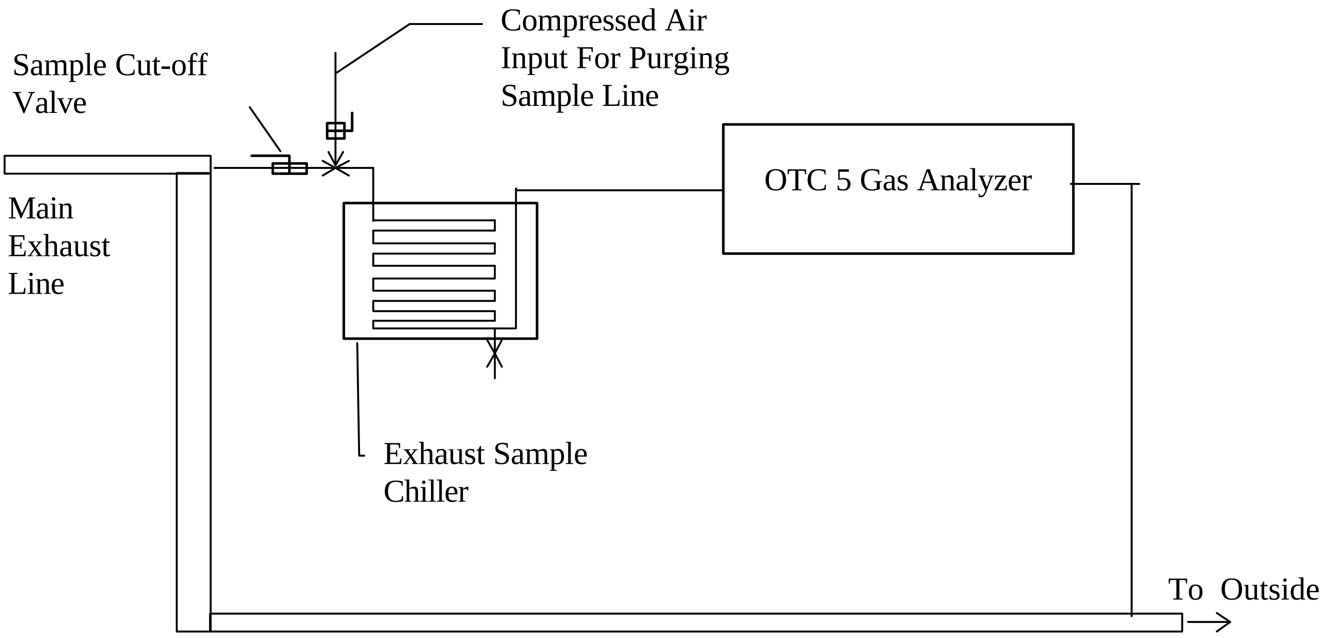


Figure 2.13 - Exhaust Sample Route

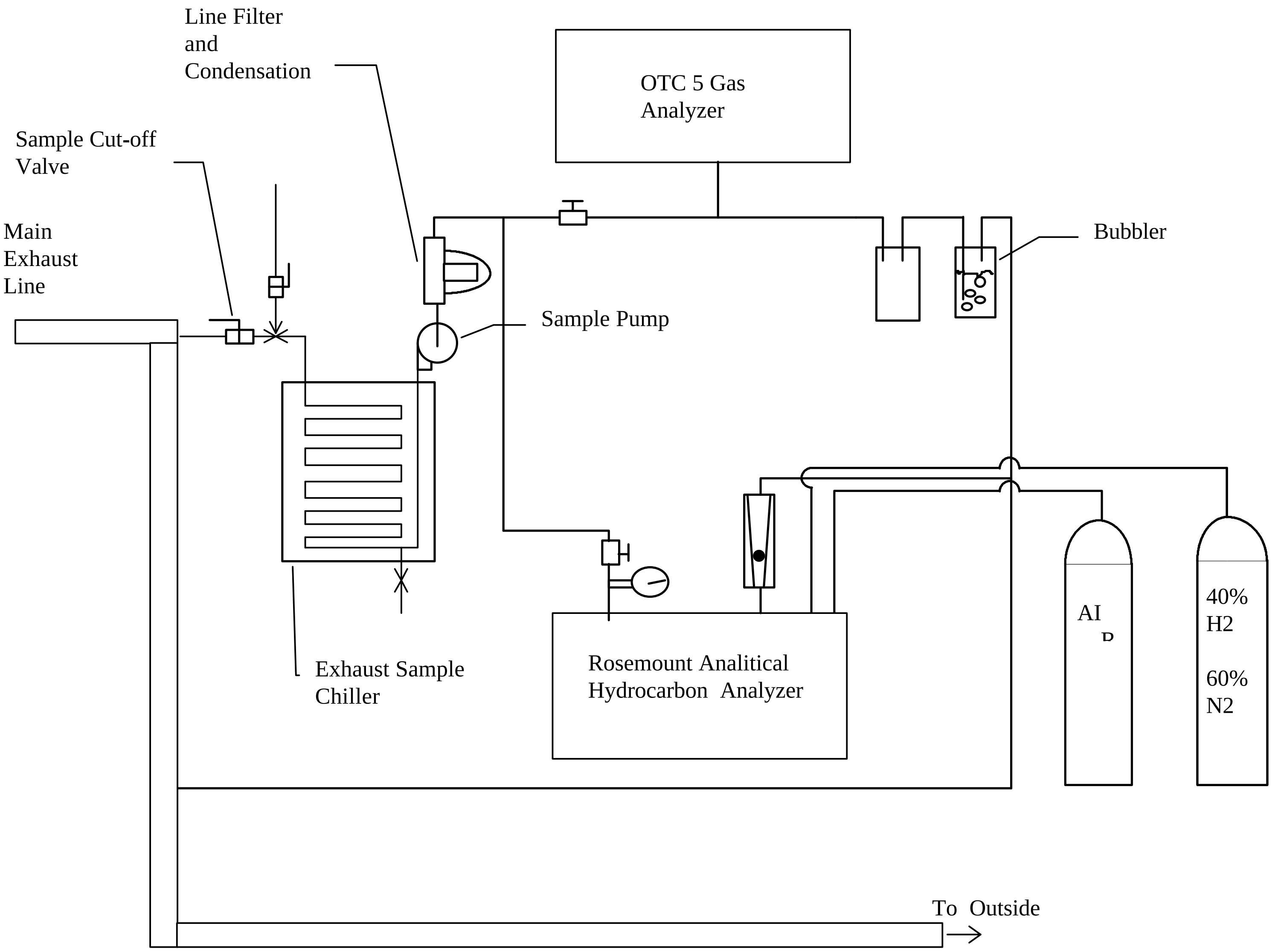


Figure 2.14 - Exhaust Sample Route #2