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The development and optimization of a hydrogen-fueled internal combustion engine

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THE DEVELOPMENT AND OPTIMIZATION OF A HYDROGEN FUELED INTERNAL COMBUSTION ENGINE

by

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ABSTRACT

The Development and Optimization of a Hydrogen-fueled Internal Combustion Engine

by

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Conventional internal combustion engines modified to burn hydrogen fuel offer a good transition mode to a hydrogen economy for transportation applications. Details are given about the development of one such approach. This effort starts with a conventional 454 cubic inch Chevrolet V-8 engine that is then modified in various ways to accommodate the use of hydrogen; including specially formed intake and exhaust passages, modified cam, and fuel injection. Because the application is for constant speed application, tuned intake and exhaust is used.

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CHAPTER 1

INTRODUCTION

This engine development stemmed from a project given to the University by the US Department of Energy to improve the performance of one of the world's first hydrogen fueled electric hybrid buses. After evaluating the existing engine system on the bus, it was decided that it would be better to scrap the original engine and begin again. Problems with the original system included low power output, high oil consumption, and unstable operation. Details of the original system and its evaluation along with references are given in the appendix.

A goal of this project was to build a hydrogen-fueled engine that addressed many of the current problems with using hydrogen as a fuel. Such problems involve knocking, backfiring, pre-ignition, and unstable operation. Special design considerations for various engine components were implemented based on studies that were performed. These components and their modifications are described later in further detail. Because of an existing relationship with a local business, Kell's Automotive [1], that has the equipment to do this type of work, most of the development was performed at their location.

Literature Review

To start this project, research was conducted into prior research to find information on previous approaches that had been tried. Several reports are found in the literature about hydrogen engine development. Mathur and Das [2] reported work on the use of hydrogen on a variable compression engine that utilized port injection. Engine speeds (1000-2000 rpm) and compression ratios (6:1-11:1) were varied while measuring engine performance. This research concluded that timed manifold injection and higher compression ratios better-utilized hydrogen's properties to increase performance and efficiency of hydrogen-fueled engines.

A paper that reported results of both an analytical study as well as an experimental study was given by Van Blarigan and Keller [3]. An Onan single cylinder diesel engine with a 14:1 compression ratio was used for this work. Their work concluded that it is possible to achieve EZEV emissions standards by operating the engine under lean air/fuel ratios at the sacrifice of power output, and high efficiency can be obtained by using a high compression ratio.

A review of hydrogen fueled engine studies has been given by Billings [4]. Included in this discussion are the effects of water injection as well as some other methods to control pre-ignition and backflashes. In addition, there are details of hydrogen vehicle prototypes that were developed by the author.

The conclusions reached when these papers are considered together were mixed. For example, several different values for the compression ratio have been applied, without a clear view of an optimal range. It is true that the effect of compression ratio on the efficiency of a basic Otto cycle is well known. What is not described in the literature to any extent is the affect of compression ratio on the operational parameters of importance, including control of pre-ignition, emissions, and fuel economy. Undoubtedly this parameter is affected by flow passage and combustion chamber design, but little information is given on the basic parameter choice.

In addition, it was found that fuel injection, while used in several of these studies, has not been clearly defined in terms appropriate applications. It is also clear that commercially available units are limited. Almost no mention of the various problems experienced with pintle-based designs was noted in the literature. Although a few researchers have touched upon it, water injection does appear to be quite beneficial from both stabilizing operation as well as decreasing emissions. However, limited quantification of this statement appears in the literature noted above. In addition, with the constant speed application, tuning of the exhaust and intake is a possibility. However, none of the papers reviewed used this type of application. Finally, current advances in computer control of the various aspects of engine operation were not really dealt with in these reports of studies.

CHAPTER 2

DEVELOPMENT PROGRESSION

Research Specifications, Goals & Objectives

After the decision was made to completely redesign the engine, the project goals were addressed. The original performance benchmark of 100 miles (161 km) at a maximum speed of 55 miles per hour (88.5 km/h) with low emissions was taken as a minimum. Using the NREL developed computer simulation program ADVISOR [5], it was estimated that at the top speed on level ground, the bus would consume around 100 horsepower (75 kW) of energy. Although a percentage of this total energy would come from the regenerative braking system, it was neglected during the engine design. The fuel efficiency of the engine was based upon the rated capacity of 33 lb (15 kg) of hydrogen within the hydride storage beds. Assuming constant operation at 55 mph (88 km/h), this would yield a maximum fuel consumption rate of 18.15 pounds per hour (8.12 kg/hr). Combining the two requirements would yield a maximum brake specific fuel consumption of 0.1815 lb/hp*hr (0.108 kg/kW*hr) at 100 hp.

To accomplish the task of redesigning the engine to meet these expectations, knowing that the hydride beds on the bus were designed to deliver gaseous hydrogen at approximately 100 psi, it became apparent that much of the development might be drawn from an existing natural gas engine developed by Kell's Automotive. The natural gas engine was designed to produce approximately 135 horsepower (100 kW) at constant speed for use with an electric generator. One of the main features of the natural gas engine that seemed applicable to the design of the hydrogen engine was the use of a custom "tuned intake" system to help increase the volumetric efficiency of the engine. It was felt that the fuel delivery system used on the natural gas engine (gaseous fuel carburetors) was inappropriate for use with hydrogen, leading to the decision to move to electronic fuel injection for the next generation hydrogen engine.

Design Progression

In early fall of 1999, one year after the bus was moved to the Center for Energy Research, the design of the new hydrogen engine began. Basing the design upon the natural gas engine developed at Kell's Automotive, we chose to use the same stock 454 big-block Chevrolet as a starting point. This included the same aluminum heads and camshaft that were used on the natural gas engines. These heads were custom made with significantly reduced intake and exhaust port diameters to match the "tuned intake" design. Some additional modifications were done to the profile of the camshaft to help reduce backfires; primarily reducing the overlap.

Many parameters of the engine needed to be established early. The most important parameter that needed to be set was the compression ratio. Research into the desired compression ratio provided a variety of results. Some researchers would indicate that lower compression (e.g. 8:1) was good for hydrogen, while others would say that higher compression (e.g. 20:1) was necessary. Without the time and financial resources available to perform our own tests for compression ratio, a value of approximately 14:1 was selected, with the understanding that this could be modified if necessary.

The next challenge came in developing a new fuel delivery system. With the decision to move to port fuel injection, an extensive literature search was undertaken to ascertain what research had already been done. It was found that the dry environment of pure hydrogen gas could lead to failure of standard fuel injector components due to the lack of lubrication. This was experienced when automotive style gasoline fuel injectors were used with hydrogen gas. The injectors would operate normally for a period and then suddenly malfunction, sometimes freezing in the open state. After an extensive search, a company was found that manufactured gas valves for hydrogen that could be incorporated into the engine design (see appendix). Since the valves were not originally intended for automotive use, special mounts needed to be made to interface them with the engine (see Figure 2–1).

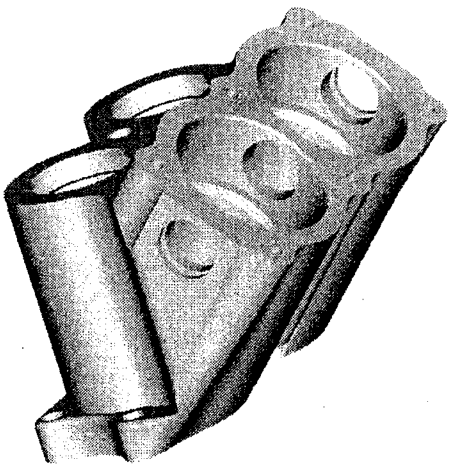


Figure 2–1 Custom hydrogen injector mount

Each mount would hold two injectors, thus requiring the machining of four identical mounts. With the four mounts in place on the manifold as shown in Figure 2–2, the fuel manifold was designed to provide a relatively large volume reservoir as close as possible to the injectors. The desire for this reservoir was to minimize the drop in fuel pressure that would occur when each injector opened. A pressure transducer was located on the fuel reservoir to monitor the fluctuations. To maintain a constant pressure differential across the injectors, a feedback pressure regulator that could compensate for changes in manifold pressure was incorporated along with a solenoid safety valve prior to the regulator.

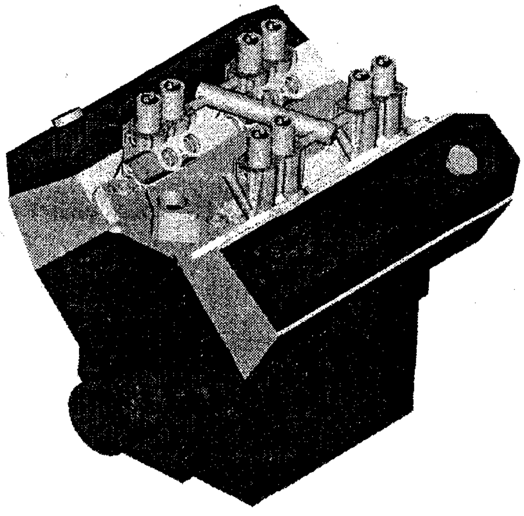


Figure 2–2 Fuel delivery system

With the fuel delivery system completed, the next task was the development of the custom "tuned intake". The tuned intake concept is derived from the harmonic oscillation of air in a tube, as in an organ pipe. The goal of tuning is to have the pressure wave created by the periodic opening of the intake valve oscillate in the intake tube and arrive at the intake valve when it opens. [6] [7] This is accomplished by varying the length of the intake runner tubes. Because the engine operates at constant speed, the frequency of oscillation will be constant; and hence the length of the tube is fixed. Since the position of the pressure wave in the tube is a function of the speed of the air in the tubes, they were chosen to have a relatively small cross-sectional area to increase this velocity. The length of the tubes was chosen based on the desired operating speed of the engine. The tubes were collected into a common plenum that was fed by a butterfly throttle. Spring-loaded pressure relief valves were made and mounted to the rear of the plenum to protect the structure upon backflash. The complete air intake system can be seen in Figure 2–3. In addition, a crankcase ventilation system consisting of an automotive air ("smog") pump connected to the center of the intake manifold was installed to prevent the buildup of hydrogen in the crankcase and possible ignition. The pump draws air from the crankcase and pumps it into the intake air to the engine. Fresh air is allowed to enter the crankcase through breathers on each of the valve covers. If these breathers are slightly restricted, it lowers the absolute pressure in the crankcase thereby reducing the pumping losses of the engine.

To control the engine, a sophisticated computer developed by Kell's Automotive was used. The system is capable of real-time adjustment of most of the engine's operating parameters such as ignition timing, injector timing, amount of fuel, etc. After various sensors and actuators were incorporated into the system, the engine was placed on the dynamometer for the first testing.

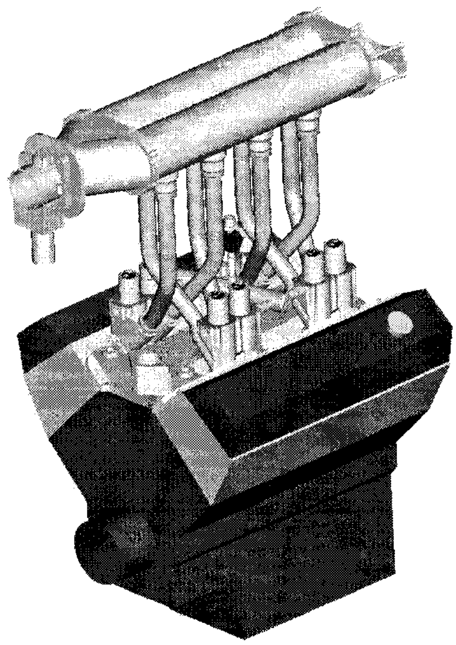


Figure 2–3 Complete air intake system

The exhaust was not designed at this point because the engine cradle that was to be mounted in the bus was not designed yet and could not be designed until the final engine configuration could be determined. For dynamometer testing, a set of tuned exhaust headers that were designed by Kell's for their natural gas engines was used.

Testing and Redesign Progression

Initial testing was done on natural gas. Because of the unconventional injectors used the engine controls computer could not handle the current to operate them. (See appendix) As a result, custom relay and power supply circuitry had to be designed for the sole purpose of providing power to the injectors. Once these items were in place engine testing could begin.

It should be noted that the engine was initially designed to operate at somewhere between 1800 and 2000 RPM to match up with the specifications for the generator. Data was typically taken for a range of values beyond this target to get a good feel for how the engine was operating. For most of the maximum power testing that was performed, the technique was as follows: The engine was warmed up with no load at a high idle (around 1100 RPM). The data

collection software was set up to take data for a given RPM. The engine was brought to a higher speed than the target under load so that the throttle could be opened fully. The load was then slowly increased in a manner that would bring the speed of the engine down through the target value where data was then collected.

For preliminary comparison, some performance data was collected for the engine running on natural gas. The data was compared with the original hydrogen engine run on natural gas and the generator engine developed by Kell's Automotive (see Figure 2–4). The comparison shows as a rather large improvement over the old hydrogen engine and a slight improvement over the engine developed by Kell's Automotive.

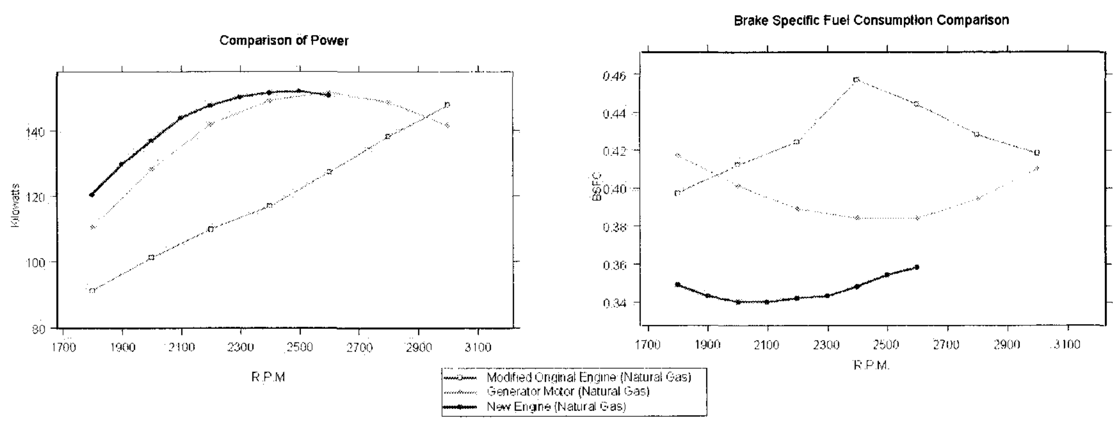


Figure 2–4 Natural gas performance comparison (Note that the BSFC is in lb/hp-hr)

Following the natural gas tests, the engine was run on hydrogen for the first time. Several control parameters needed to be adjusted to convert to running on hydrogen, such as the ignition and injector timing, as well as the injector open times, but the process was relatively simple due to the nature of the computer control and associated software. Once these values were set under a no load condition, a load was placed on the engine. It was found that above a certain load the engine began to produce back-flashes and pre-ignite. Back-flashes are an extreme form of pre-ignition where the fuel air mixture is ignited before the intake valve in closed. Unfortunately, the point at which this began was below the targeted power output of the engine.

Since this problem is typically a result of a hot spot or residual heat within the combustion chamber, the first attempt at reducing the pre-ignition was to use spark plugs with a colder heat range. This seemed to help, but not enough. The ground electrodes were removed from a set of spark plugs and this seemed to help even more, but still not enough. In an effort to dissipate the residual heat left in the combustion chamber after the exhaust stroke, the injector timing was retarded as far as possible to allow the fresh air charge time to cool the chamber before injection of the fuel. Also to further cool the engine and hence the combustion chamber, the water pump, heat exchanger, and thermostat were removed and cold tap water was passed directly through the engine. This lowered the coolant exit temperature from about 145 degrees to 120 degrees and significant improvement followed. Never the less it was still not enough to maintain power over longer durations (several minutes).

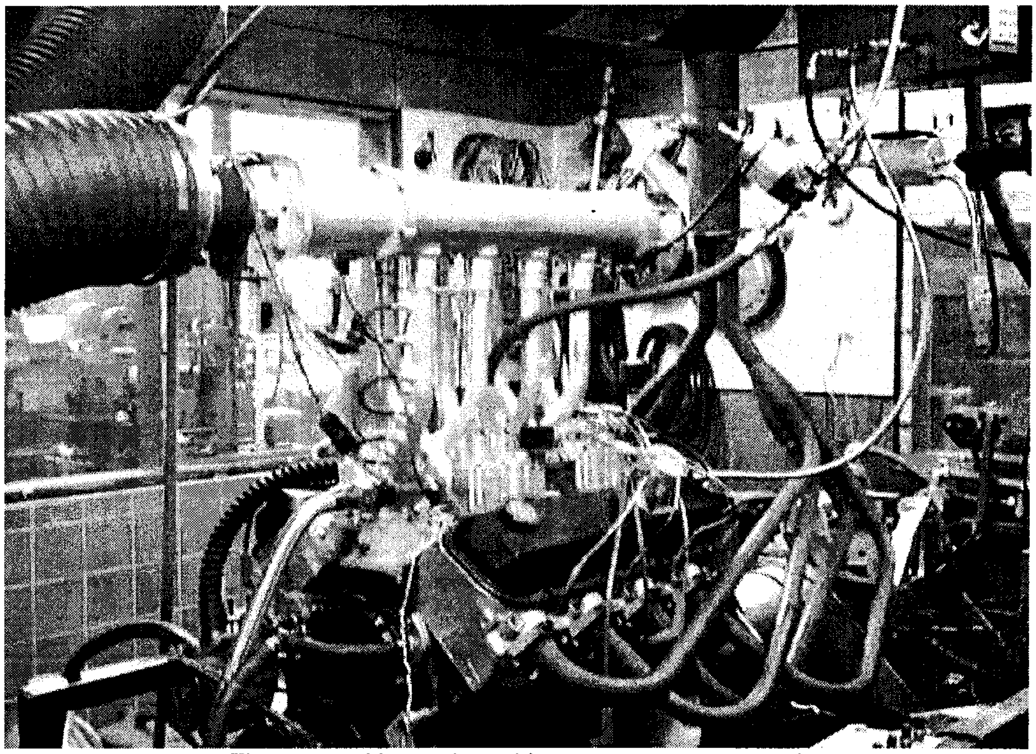


Figure 2–5 H2 engine with water pump removed

At this time, it was also observed that the fuel injection duration was beginning to overrun the intake cycle. To remedy this, the fuel pressure was increased to increase the flow rate of the injectors, but the fuel injectors could not open against the pressure that would be necessary to achieve the mass flow rates required. The fuel injectors were then disassembled and the effective port area was increased by approximately 80%. Following the modifications, the injector duration was significantly reduced to well below the allowable intake window. Using this setup, a number of tests were performed using the engine on the dynamometer to determine a number of optimal operating conditions, such as the best value for the ignition and injector timing. It became apparent that air/fuel ratio is a parameter that needs to be controlled easily and accurately. Therefore, an oxygen sensor feedback system was incorporated into the electronics to control the air/fuel ratio precisely at any chosen value. This also made it easy to do comparison tests at different ratios.

When the water pump and heat exchanger were installed back into the system, the engine appeared to perform better than it did initially, but still not good enough to meet the project specifications. The option of using exhaust gas recirculation and or operating the engine in a lean condition to eliminate the pre-ignition and back-flashes was discussed. Both were tried with less than desirable results. Lean operation was first because of its ease of implementation. As expected, the results of operating the engine at leaner than stoichiometric, made the engine increasingly stable while reducing NOx emissions. However, with this increase in stability, the power output of the engine fell off drastically. The engine simply could not make enough power to meet the objectives set in the beginning of this project.

Exhaust gas recirculation was tried next. The thought was that with EGR the engine could be operated at stoichiometric while using just enough EGR to control the pre-ignition. Again, similar results, the engine operated stably at wide-open throttle with lower emissions that without EGR but, the power output was substantially lower than the level required. After some examination, it became apparent that what was needed was a method to control pre-ignition without displacing large volumes of hydrogen in the combustion chamber, which is what both lean burn and EGR effectively do.

After considerable debate because of the challenges that its implementation produces, it was decided that water injection should be tried on an experimental basis to see if this could combat the pre-ignition. The theory behind water injection was that the finely atomized water droplets that were introduced into the incoming air would vaporize, thus absorbing much of the heat that would normally trigger the pre-ignition. This in fact worked, and it worked better than expected. By simply spraying atomized water into the intake air, the tap water cooling was no longer necessary. The engine could now produce in excess of 75 kW at 1800 to 1900 RPM while consuming as little as 2 gallons of water per hour, which has the possibility of being recovered from the exhaust which has a high concentration of water vapor from the hydrogen combustion. These results are directly comparable to the results that Billings published in his book. He reported that with the proper ratio of water to hydrogen in the combustion chamber, not only would it bring the pre-ignition under control, it would significantly reduce NOx emissions.

Once this was accomplished, a few tests needed to be run using the generator, so the engine was removed from the dynamometer and coupled with the generator on a special test stand. A resistive load bank capable of up to 250 kW was used as a load on the generator, thus simulating the actual operation of the engine. Now a throttle control system needed to be developed to hold the engine speed constant, because in operation the engine would be run at a constant speed. Looking at the various data collected thus far, including the volumetric efficiency graph shown in Figure 3–3, and the operating range of the engine it appeared that the optimal operating point was around 1900 RPM. Electronic throttle control was thus incorporated into the control computer to hold the engine at a constant speed, regardless of load.

The exhaust gas analysis and emissions numbers have not been discussed thus far. This is due mostly to the seemingly erratic behavior of this data through the initial testing due to a number of factors, including the fact that whenever the air-fuel mixture would ignite prematurely, the high cylinder pressures and temperatures created by the pre-ignition would increase the level of NOx emissions significantly. Also the many changes made to the engine to get it to run smoothly would effect the emissions levels, and it was felt that getting the engine to run smoothly took precedence over getting the emissions values to within the acceptable range. Once the

engine was running smoothly, it was found as discussed earlier, that the water injection contributed significantly to the reduction of the NOx levels in the exhaust. The ignition timing also played a large role in the emissions, as well as the air/fuel ratio. Figure 2–6 shows a characteristic trend as the engine was warmed up and loaded with minimal water injection.

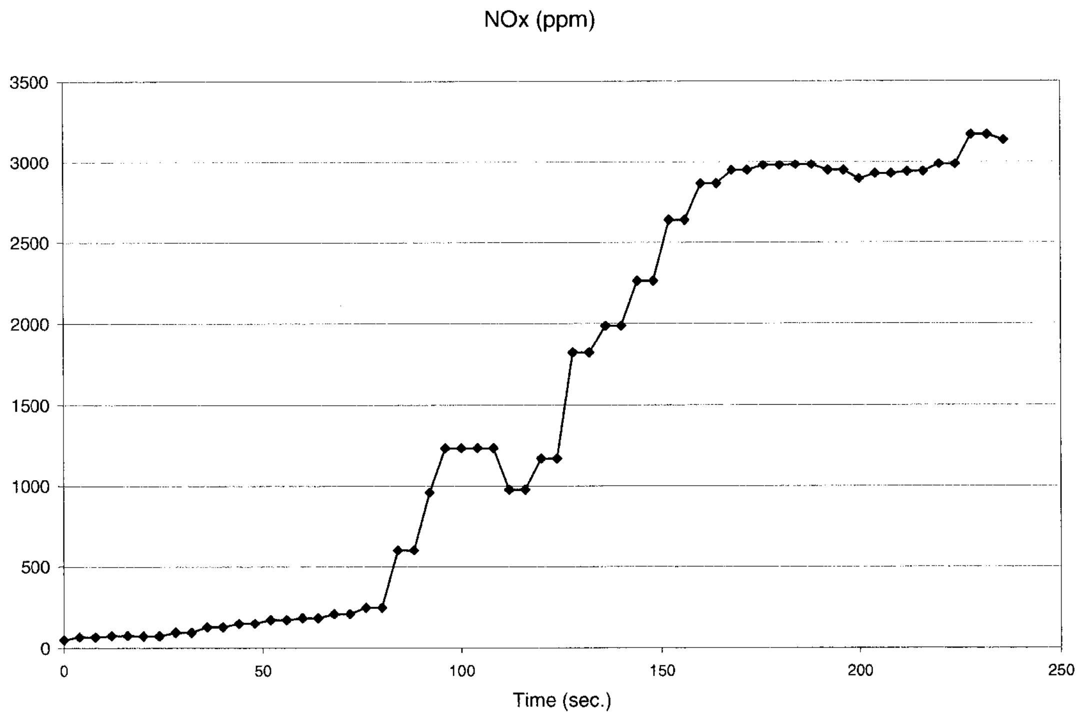


Figure 2–6 Preliminary NOx emissions numbers

Catalytic converters are used to reduce NOx emissions, however a major obstacle in catalytic conversion of exhaust gases on a hydrogen engine is the inability to operate the engine in the lean state and still utilize the catalytic effect. The catalyst requires a small amount of hydrogen in the exhaust, which normally comes from hydrocarbons, to complete the catalytic reaction. For preliminary emissions tests, a catalyst from one of the generator engines at Kell's was used to evaluate its effectiveness. Fortunately, these tests showed that the reduction through the catalyst is greater than the reduction gained by leaning out the air/fuel mixture. If some EGR was added

in to the system, the effect should be to reduce both the NOx levels and the power output of the engine. It may hold promise for reducing the emissions even further in the future.

The hydrogen engine was now tested with all of the associated systems on the dynamometer to determine the characteristics as shown in Table 2—1.

Table 2—1 Hydrogen engine characteristics

Parameter	English	SI
Operating Speed	1800 rpm	1800 rpm
Equivalence Ratio	1.06	1.06
Ignition Timing	3 ATDC	3 ATDC
Percentage EGR	0%	0%
Compression Ratio	13.6:1	13.6:1
Maximum Torque	>300 ft-lb	>407 N-m
Corrected Maximum Power	>120 hp	>89 kW
Operating Torque	273.3 ft-lb	370.5 N-m
Corrected Operating Power	105.1 hp	78.37 kW
Brake Mean Effective Pressure	89.5 psi	617 kPa
Fuel Consumption	15.6 lb/hr	7.08 kg/hr
Water Consumption	2 gal/hr	7.6 L/hr
Volumetric Efficiency	55.3 %	55.3%
Emissions of NOx (no load)	<12 ppm	<12 ppm

Now that the engine configuration had been determined, the engine cradle and a set of exhaust headers that would fit it could be designed. The design intent of the cradle was to have something that the engine-generator combination could mount to that could be removed from the bus as a unit relatively easily. This required a substantial redesign of the rear of the bus that included enlarging the rear access door to the engine. The exhaust headers were next. Their design is similar to the design process of the intake tubes with the opposite desired effect, to help scavenge the exhaust gasses from the cylinders. The catalysts used are standard automotive three-way catalysts of a style used in compact cars.

To have better control of the water injection and to automate the system a solenoid control valve was incorporated into the system. The engine controls computer drives this valve via pulse-width modulation. The optimal water/fuel mass ratio reported by Billings is around 5:1; this results in a water flow rate of approximately 35 liters per hour, which was not capable with this system. In addition, it was found that if water is being injected when the engine was shut down, restarting would be difficult because the spark plugs would be damp so the computer was configured to shut off the water at idle.

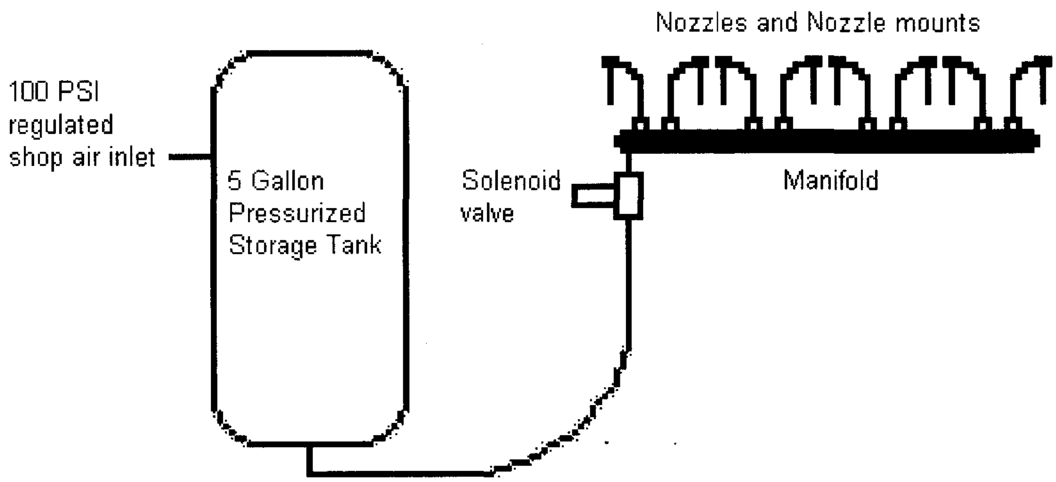


Figure 2–7 Schematic of water injection system

The engine, generator and all components were now assembled on the cradle and the system now appeared as it would in the bus. Extensive operation / testing was now done to verify that the systems would operate consistently and reliably. One issue that kept arising was the stability of the engine speed controller that was incorporated into the controls computer. Design is difficult in this case because the load applied on the engine by the generator is a function of the speed of the generator and hence the engine. As engine RPM dropped the load would relax and the governor would tend to over compensate and over shoot the RPM target and oscillation would ensue. A significant amount of time and effort was spent on trying to resolve this issue. Another problem that arose was the build up of hard water deposits in the water

injection nozzles, which would eventually clog the nozzles necessitating removal and cleaning. This was resolved by using de-ionized water in the system. Ideally the pure water in the exhaust would be condensed and used for this purpose, however funding for this project had stopped by this time and this could not be implemented. The engine was then placed on the dynamometer to get the final performance numbers.

CHAPTER 3

ENGINE COMPONENT DESIGN DETAILS

The Overall Engine

The development of the hydrogen internal combustion engine necessitated the modification of a number of stock components as well as the creation of many custom parts. A list of the modified stock components used is shown in Table 3—1

Table 3—1 Modified components

Item	Vendor	Description	Modifications
Engine Block	Chevrolet	Big Block V-8	Bored 0.030" over
Cylinder Heads	Kell's	Aluminum, 1.25 diameter ports	Smoothed combustion chambers, upgraded valve stem seals
Camshaft	Kell's	Used in natural gas engines	Decreased overlap
Manifold	KAM Products	Intake manifold base used on natural gas engines	Modified to accept injector mounts
Electronic Throttle	GM	Throttle body	Modified return spring configuration
Fuel Injectors	Hoerbiger	Hydrogen Gas Valves	Increased port area
EFI Computer	Kell's	Control unit for the engine	Reprogrammed for governor, water injection and other

The starting point for the engine was a stock Chevrolet industrial big block. The cylinders were bored 0.030" over to true them up and aftermarket pistons were added to bring the compression ratio up to 13.6:1 when combined with the heads used. The final displacement achieved was 460.4 cubic inches. The camshaft used was a derivative of the one used in Kell's natural gas engines. The valve overlap was reduced along with a small change in the profile to

help combat backfires. The stock Chevrolet valve train was used. The heads were aluminum Dart heads with 1.25" diameter ports to match the intake and exhaust tubes.

A list of the major custom parts that were created for this engine is shown in Table 3—2. The bulk of the manufacturing was performed using both manual and CNC milling and lathe tools at Kell's Automotive.

Table 3—2 Custom components

Item	Description
Injector Mounts	Mount to the intake manifold to hold two fuel injectors and two intake tubes
Intake Tubes	Equal length runners between intake plenum and injector mounts
Intake Plenum	Dual tube plenum connecting all 8 intake tubes and the throttle body
Fuel manifold	Small reservoir located centrally between the injector mounts
Water Injection Nozzle tubes	Brass tubes located in the intake plenum to locate atomizing nozzles above each intake tube
Crank Case Relief Valves	Pop-off valves located on the valve covers to relieve pressure in the event of hydrogen ignition in the crank case
Intake Manifold Relief Valves	Pop-off valves located on the rear of the intake plenum to release pressure during backfire
Exhaust Headers	Custom tuned exhaust tubes to route exhaust gases away from engine compartment
Injector Driver Circuitry	Circuitry necessary to drive the hydrogen valve fuel injectors
Extended Range 02 Circuit	Circuitry necessary to drive an extended range O2 sensor for running at non-stoichiometric air/fuel ratios

Fuel Delivery

The fuel delivery system is built around a set of eight Hoerbiger GV22 Gas Port Injectors (see appendix). To incorporate the injectors into the engine, special mounting hardware was developed (see Figure 3–1 & Design Progression section). The mounts were manufactured from solid aluminum using CNC machining. Once complete, the mounts were attached to the manifold (see Figure 3–2).

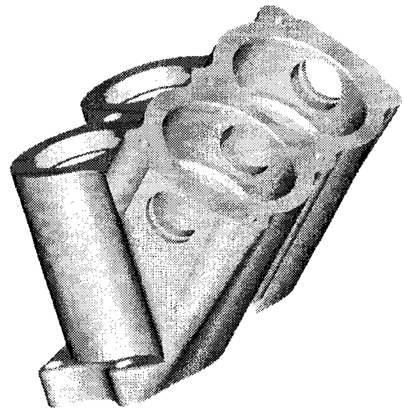


Figure 3–1 Custom injector mount

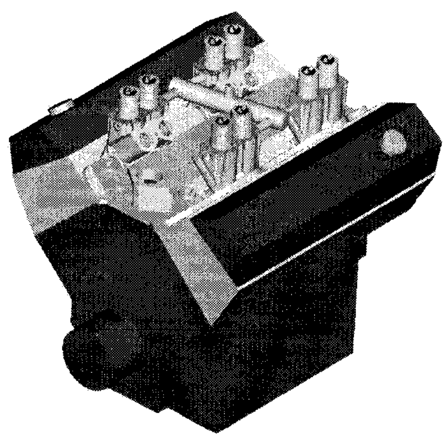


Figure 3–2 Fuel delivery system

Since this engine operates on gaseous hydrogen, the mass of hydrogen introduced into the combustion chamber is a function of both the injector on time and the fuel supply pressure. To ensure that the pressure of the fuel supply was as constant as possible, a common reservoir was utilized to compensate for the drop in pressure that would occur upon the sudden opening of the injectors. This reservoir and the tubes running to each mount were made from stainless steel and welded into a single unit. The incoming fuel line was attached at the center of this reservoir. Immediately prior to the reservoir was a high-flow feedback pressure regulator. This regulator compensated for changes in manifold pressure, thus providing a near constant pressure differential across the fuel injectors. During testing the regulator was set to hold the fuel pressure

at approximately 48 psi (331 kPa) above the manifold pressure. Also included in the fuel supply line is a normally closed solenoid safety valve.

Air Intake

The use of a gaseous fuel such as hydrogen or natural gas presents some interesting challenges. One of these challenges lies in the fact that the fuel occupies considerably more volume within the combustion chamber than does a liquid fuel such as gasoline. This typically reduces the amount of air that can be drawn into the cylinder by a similar volume, thus decreasing the power output of the engine. For a stoichiometric mixture of liquid gasoline to ignite, a volumetric ratio of about 5 percent fuel to air is required. In contrast, for a stoichiometric mixture of hydrogen to ignite, a volumetric ratio (at atmospheric pressure and temperature) of approximately 39 percent fuel to air is necessary. The volumetric efficiency at wide open throttle of an engine run on gasoline and then on hydrogen should therefore decease by this ratio from around 95% for gasoline to 61% for hydrogen. This corresponds to a decrease in power of around 38%. To attempt to recover this loss in power, the use of custom intake ports and runners has been employed to create a natural supercharging effect. The results of this customization are shown for different equivalence ratios in Figure 3–3.

To accomplish this "natural supercharging" some basic principles of wave dynamics were employed. The port diameter was actually decreased to increase the velocity of the air traveling inside the intake tubes. The major alteration over a typical intake manifold is the use of long runners between the common plenum and the intake valve. The centerline length of this tube was established from calculations based upon the harmonic oscillation of air in the tubes. The desired effect was to have air pushed into the cylinder when the intake valve was opening, thus creating a slight supercharging effect. As can be observed in the figure, the volumetric efficiency appears to have a peak around 1900 to 1950 RPM that is in accordance with the speed for which the tuning was calculated. It can also be observed that the volumetric efficiency is significantly higher than the calculated maximum efficiency of 61% for a typical air intake system. Figure 3–4

is a drawing of the original design and Figure 3–5 is a photo of the finished system early in the project.

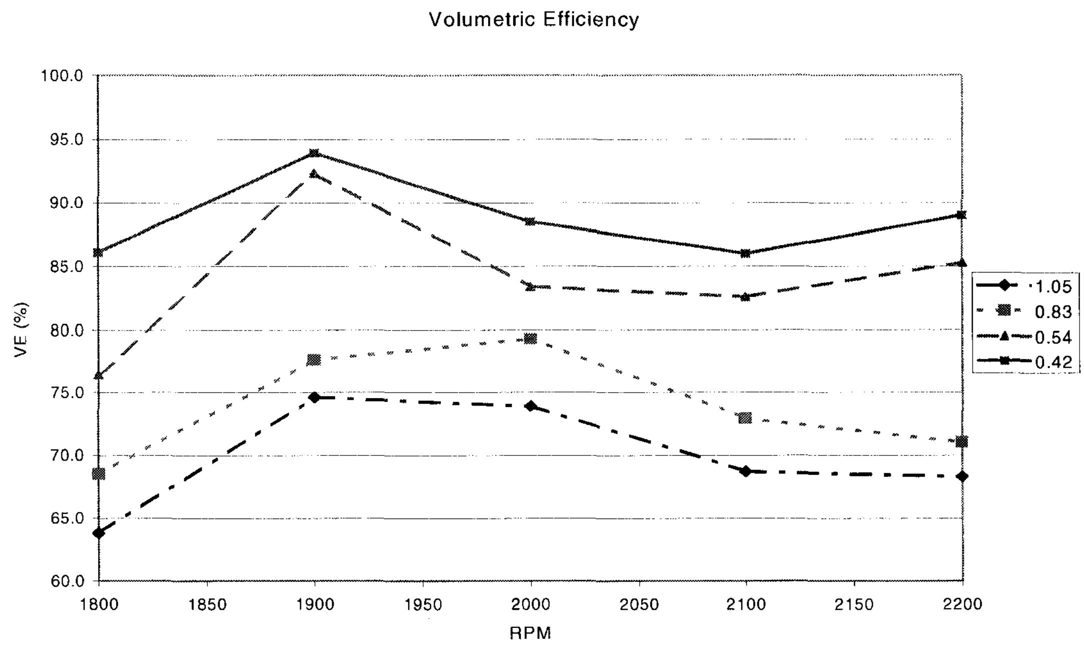


Figure 3–3 Volumetric efficiency of the tuned intake at various equivalence ratios

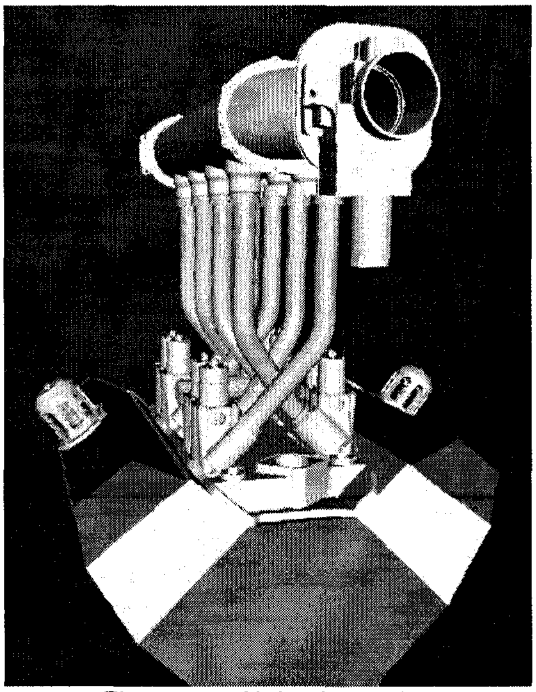


Figure 3–4 Air intake design

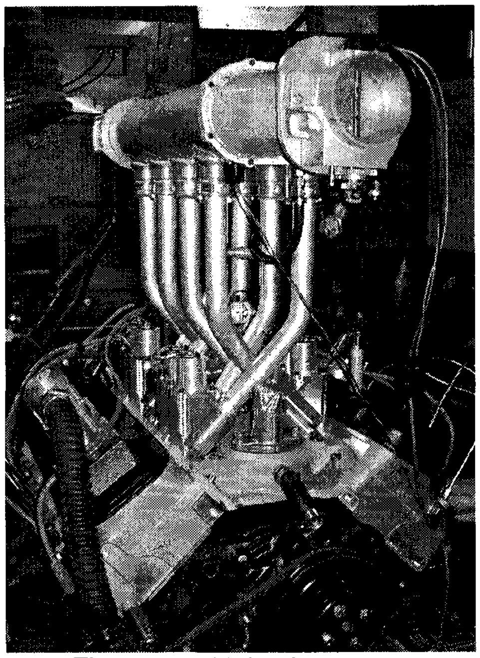


Figure 3–5 Air intake system

The plenum located at the top of the tubes was designed to provide a large volume of near constant pressure from which the individual cylinders could draw air. The design has a convergent section at the front of the engine to join the two tubes and to accommodate the butterfly throttle. On the rear of the plenum are two spring-loaded pop-off pressure relief valves to relieve the pressure during a backflash. An assembly drawing of the plenum is shown in Figure 3–6.

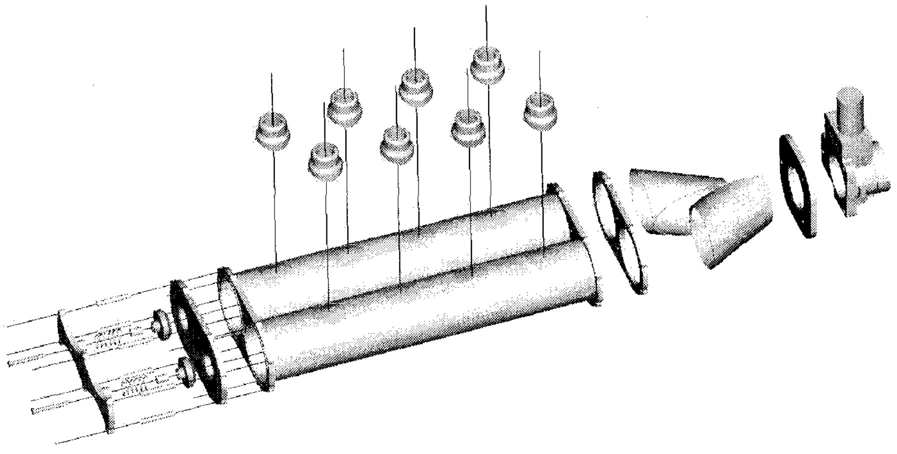


Figure 3–6 Air intake plenum assembly

Electronic Control

The ECM (Engine Control Module) that was provided by Kell's Automotive was central to the operation of the hydrogen engine. The central computer was housed in an aluminum case that included three weather-tight connectors for input and output. Two supplemental units were included to drive the special fuel injectors, and a third for linearizing the O2 signal. Below is a list of the items that the computer controlled or monitored:

Table 3—3 Computer controlled parameters

Controlled	Monitored
Operating Speed (RPM)	Throttle position
Air/Fuel Ratio	Cylinder Exhaust Temperatures
Fuel (RPM & MAP based)	Coolant Temperature
Fuel percentage per cylinder	Intake Manifold Absolute Pressure
Ignition Timing	Intake air Temperature
Injector Timing	Crank Angle
Spark	Exhaust O2
	Oil Pressure

The ECM monitors these engine parameters and operates the engine based on them. It does this by carrying on board a saved parameter table that contains the fuel and timing maps as well as any set values such as when during the intake stroke to inject the fuel. RPM is obtained using a proximity sensor that senses teeth on a wheel mounted to the front of the engines' crankshaft. Engine cycle position information is gained by using an inductive pickup located on the #2 spark plug wire (the use of the #2 wire is because it is the cylinder that is just before #1 in the engines' cycle). All of the values in this table can be adjusted during engine operation. This is done with a PC that can be connected to the ECM using fiber optic communication cables or a standard null-modem serial cable. Fiber optics is used to eliminate noise in the signal to and from the ECM due to the ignition system on the engine. Once these parameters have been optimized, the PC can be disconnected and the ECM acts as a stand-alone component.

The fuel map that is stored in the parameter table tells the computer how much fuel to deliver, based on manifold pressure (load) and RPM. This gives rise to a matrix that can be as large as 32 by 32. Hence, the engine RPM and manifold pressure operating ranges can be divided up into 32 increments each. This provides for very fine-tuning of the quantity of fuel delivered to the engine. For values of operation between these increments, the value used is interpolated. To ensure consistent Air/fuel ratio, exhaust gas oxygen is monitored. The computer compensates for deviations in the desired air/fuel ratio by adjusting the operating value in the fuel map. The desired air/fuel ratio is also mapped as a function of manifold pressure and RPM.

Ignition timing map is similar to the fuel map in that it is a function of RPM and Manifold pressure. This ignition-timing matrix can be as large as 8 x 8, which provides for fine-tuning of the ignition advance curve for the engine as a function of load as well as RPM. Typical ignition systems advance as a function of RPM only.

Water injection is also controlled via the same kind of table that is based on manifold pressure alone because it is directly comparable to the load being applied on the engine. The user specifies a threshold RPM above which the values entered for the corresponding manifold pressures are in percentages of the duty cycle for the solenoid valve.

The fuel-injector timing table is based on RPM alone. The values entered are in degrees before top dead center. The computer compensates for the injectors' inherent turn on delay by advancing the open signal to the injector proportionally to the RPM. This ensures that the start of the injector duration occurs at the same point in the intake cycle throughout the RPM range.

The ECM also has a governor function. A small DC motor has been attached to the throttle. Throttle position is controlled using a pulse width modulated signal sent to the motor; spring force is used to close the throttle.

Data logging is another function of the ECM. The signal from any sensor that is monitored by the computer is recorded and stored internally in Memory built into the computer. This data can then be downloaded into a PC for viewing. The sample rate is dependent on the individual signal. The more dynamic signals like manifold absolute pressure are recorded every cylinder firing. The less dynamic signals, like barometric pressure, are recorded less often.

Water Injection

To combat the pre-ignition and to reduce NOx formation, a custom water injection system was designed and tested. The concept of water injection for hydrogen internal combustion engines has been researched before. Drawing largely from the findings in the previous research, it was hypothesized that the implementation of such a system on this hydrogen engine might cure some of the problems. The intake manifold (Figure 3–7) was fitted with Bete PJ-10 atomizing nozzles. The nozzles were located above each intake tube very near the throat of the tube. Custom mounts were made to hold the nozzles in this position (Figure 3–8). The water is controlled via a solenoid valve, and is stored in a 5 gallon pressurized storage tank. The solenoid valve is controlled by the computer to turn the water injection on once the engine reaches a user specified RPM and then according to manifold pressure. To pressurize the tank, compressed shop air was connected to the inlet of the tank and the pressure regulator was set to the desired pressure.

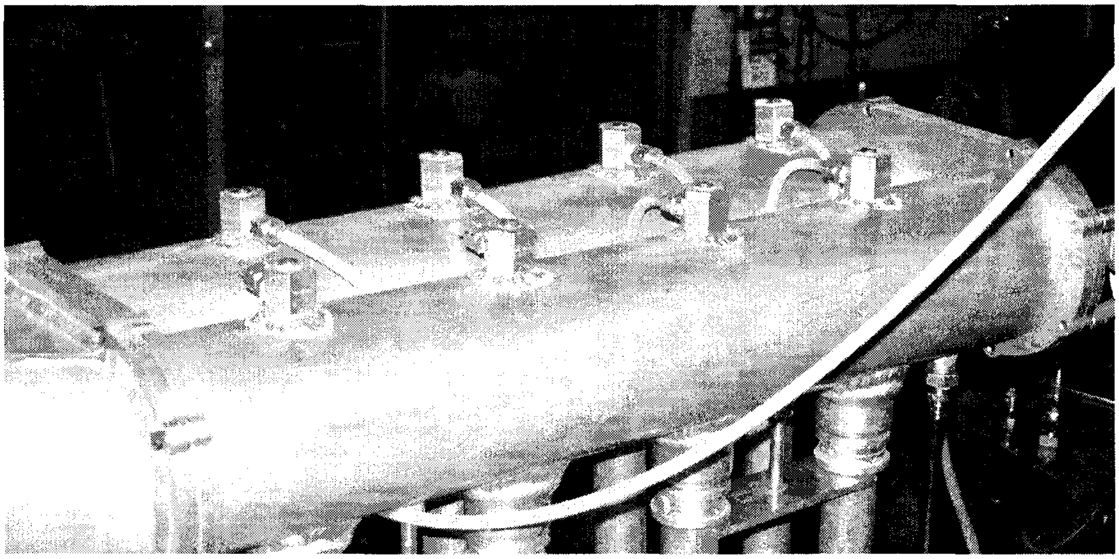


Figure 3–7 Water injection system

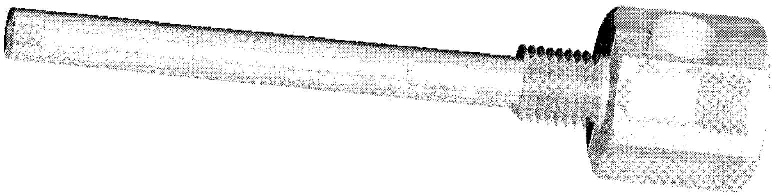


Figure 3–8 Nozzle mount

Extensive testing was performed to determine the pressure versus flow rate characteristics of the water injection nozzles. Following the determination of the effects of water on eliminating pre-ignition, the pressure (and therefore flow rate) was increased to qualify the effect on the NOx levels. Some results are presented in Figure 3–9. The data presented by Billings is shown for comparison as the theoretical points. The difficulty with using water injection to eliminate NOx is due to the relatively large quantities of water necessary. It is hypothesized that if enough water were introduced, the temperature within the combustion chamber would never reach the levels necessary for NOx formation. This engine would require as much as 5 gallons per hour, possibly even more. Unfortunately, our testing apparatus was not capable of achieving flow rates above approximately 3 gallons per hour. Care has to be taken under these higher flow rates not to contaminate the engine oil with water. It was observed during testing that if large amounts of water were used during short operation times the oil would not get hot enough to vaporize the water that managed to get in the crank case and would collect there.

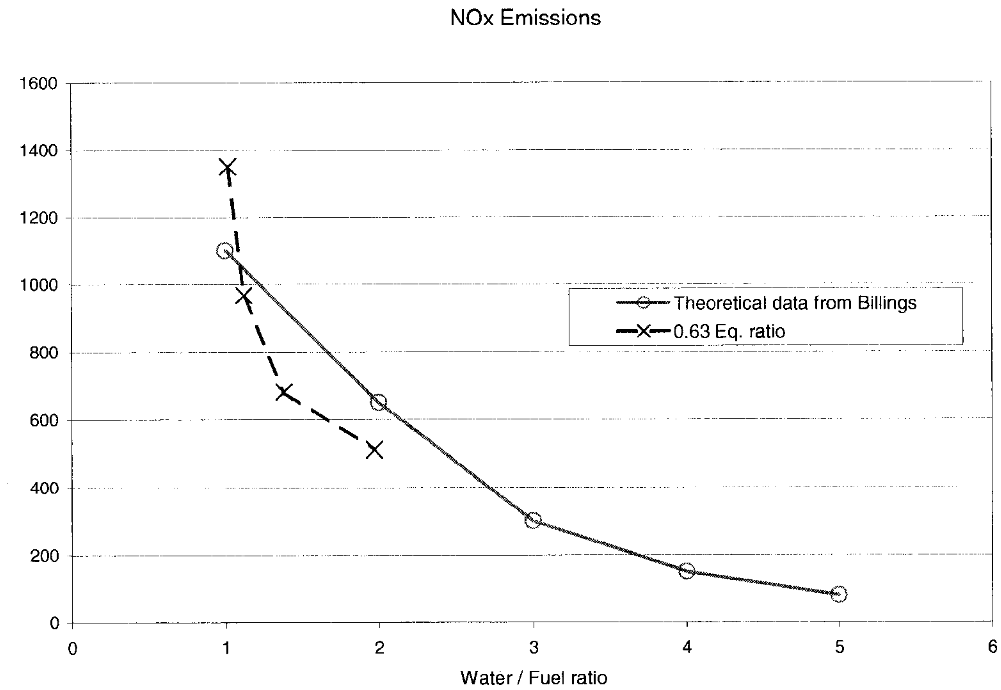


Figure 3–9 Effects of water on NOx emissions

Exhaust

The exhaust headers were designed using computer-modeling software that allowed the length of each runner to be matched to within an inch. This equalization of runner length has a similar effect to that of the intake runner in that it will establish a harmonic oscillation that will assist in removing the exhaust gases from the combustion chamber. Each set of four headers enters a collector, which then enter a common chamber in which the oxygen sensor is located for direct feedback of the air/fuel ratio of the engine. Ports were also placed in this section to allow direct gas sampling for emissions analysis. After this section, the tubing diverges into the catalytic converter section. The catalysts used are standard automotive three-way catalysts of a style used in compact cars. They are approximately 4 inches in diameter and the length of the catalytic monolith inside is approximately ten inches. Because of the compact units chosen, two were placed in parallel to slow the exhaust gas velocity to help ensure catalytic completion. The converters are standard automotive three-way catalysts. From there, the exhaust moves through the muffler and tailpipe.

CHAPTER 4

PERFORMANCE

Performance Comparison

The data shown in Figure 4–1 is a comparison of the initial data that was collected when the engine was first operable before the custom exhaust was completed and the water injection system had been refined and the final data from the completed engine. Corrected values are used because the data sets were taken months apart.

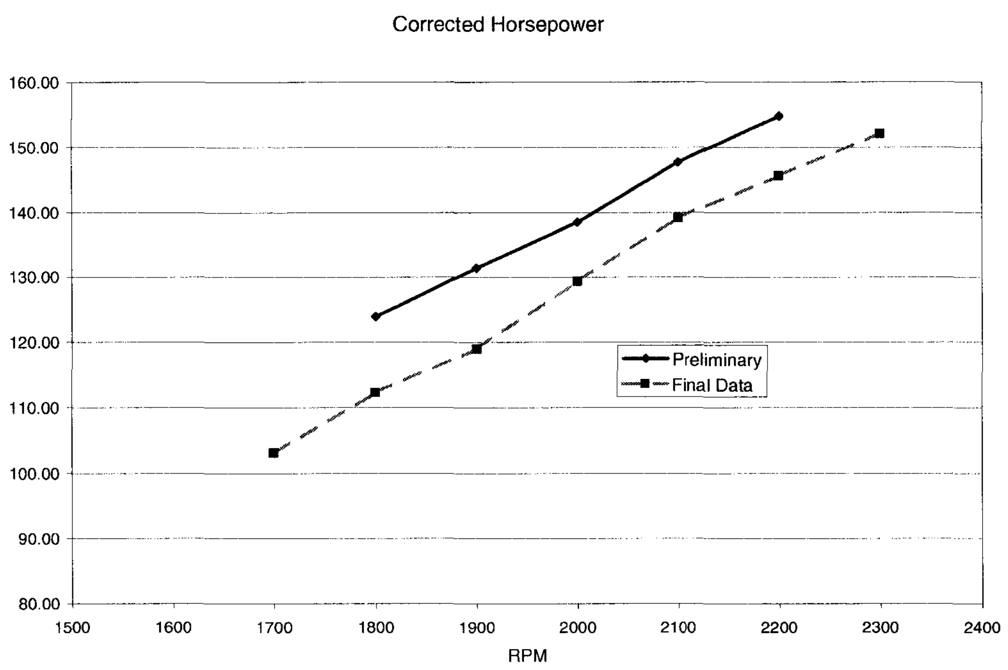


Figure 4–1 Horsepower comparison

The decrease in power is due to the physical space constraints on the exhaust system that were imposed by the engine compartment of the bus. The exhaust headers that were used for

the preliminary tests had minimal bends with large radii and merged into an oversized collector that fed into a large catalyst/muffler. (Figure 2–5) The exhaust system that was created to fit in the engine compartment of the bus had many more bends and utilized smaller catalysts and muffler. (Figure 5–3) Even with this decrease in power the lowest point on the curve exceeds our design goal. While the data for both of these curves is taken in short periods for each point, the engine in the final state could be held at these conditions indefinitely which was not the case initially due to pre-ignition and backfires. The numbers given here are comparable to the natural gas performance numbers given earlier. This was a concern because of the larger volume that hydrogen occupies for the same amount of energy.

The effect of the addition of the constrained exhaust system is evident in Figure 4–2. This conclusion is drawn from the fact that there were no changes to the physical makeup of the engine other than the replacement of the exhaust system and the addition of the water injection system. If this change was due to the injection of water, the change should happen over the entire RPM range, not just at a narrow band in it.

Even with this decrease in volumetric efficiency and power, the fuel efficiency and hence the thermal efficiency of the engine increased as can be seen in Figure 4–3. This is due to the fine-tuning of the various operating parameters such as the fuel map over the duration of the testing that occurred and the addition of water injection.

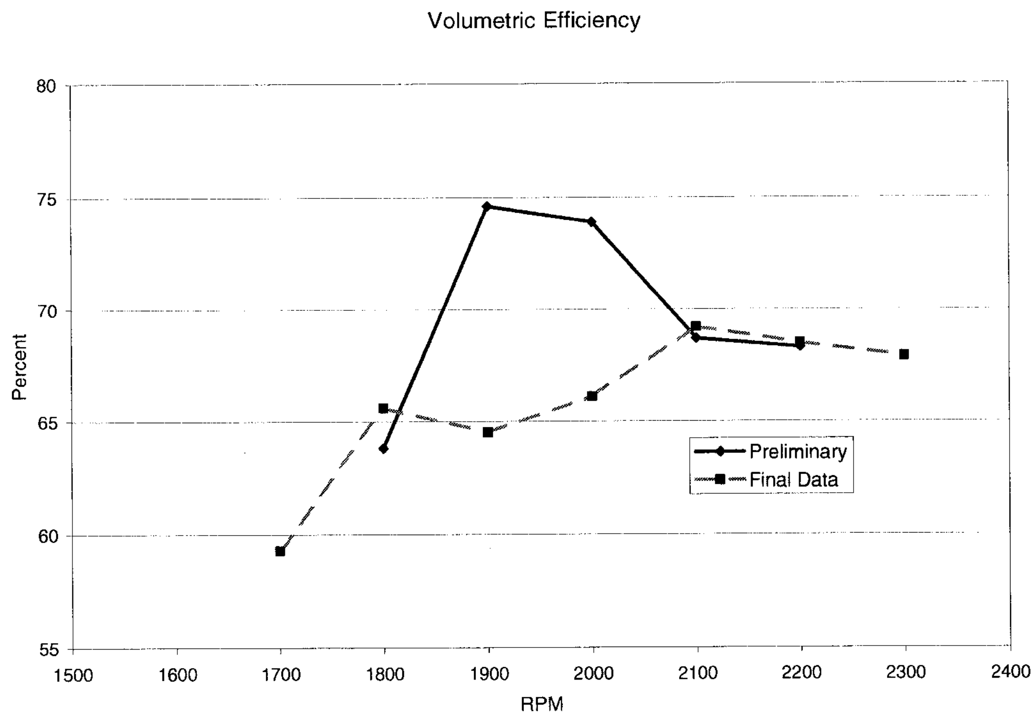


Figure 4–2 Volumetric efficiency

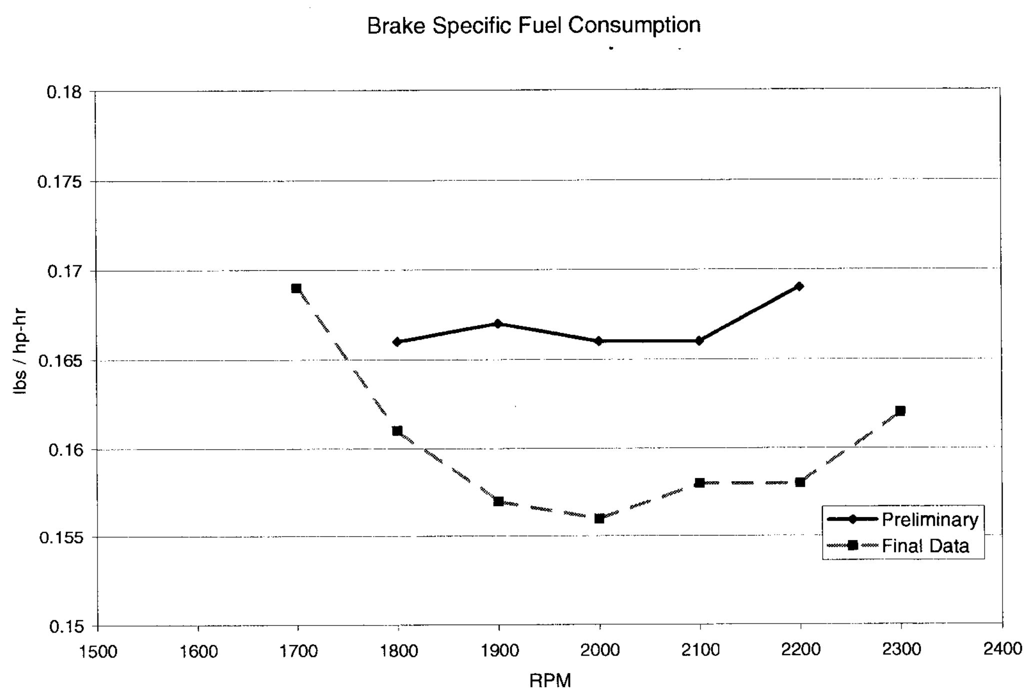


Figure 4–3 Brake specific fuel consumption

Emissions

Figure 4–4 shows a comparison of the pre and post catalyst NOx levels for the finished hydrogen engine at constant load conditions. These values are averaged over a couple of runs where some time was allowed during each run to reach semi steady-state operation. The engine was operated at a slightly rich air/fuel mixture to take advantage of the catalytic process. Because there are no hydrocarbons in the exhaust, there has to be some excess hydrogen present to convert the NOx into Nitrogen and water. As can be seen the use of catalytic converters on this engine reduces the emissions by about 30%. Lower emissions might be possible with increased water injection, which is not possible with this system. With increased water however, the possibility of oil contamination increases as well. For this data, the water injection system was wide open at 100-psi line pressure with no indication of oil contamination at the end of the runs.

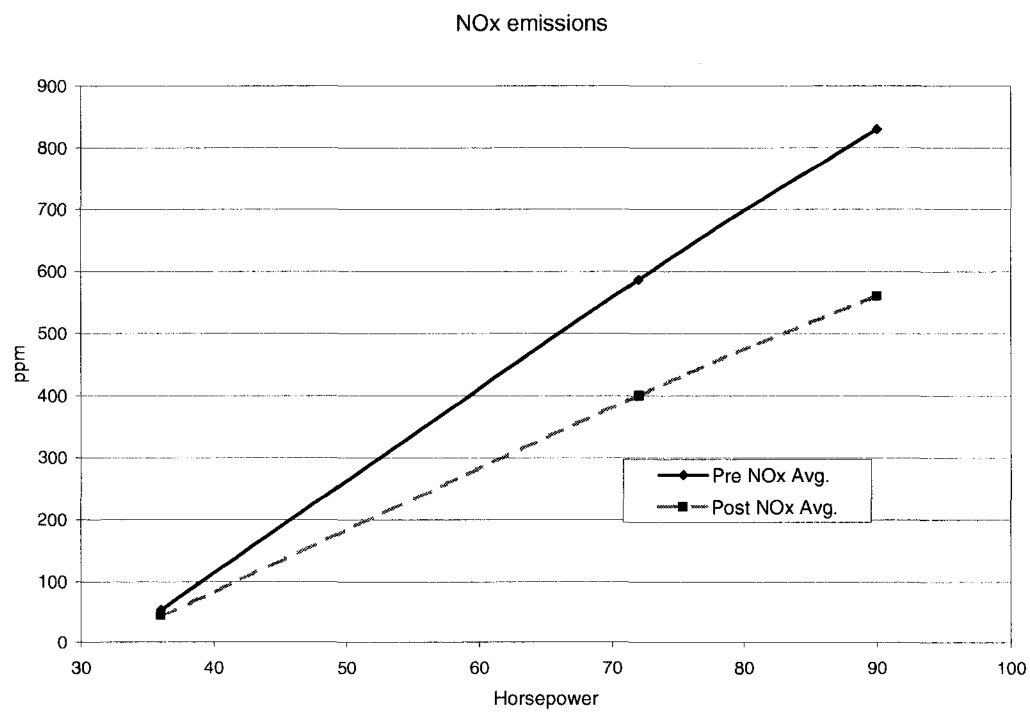


Figure 4–4 NOx emissions

CHAPTER 5

OVERVIEW OF ENGINE INSTALLATION AND BUS SETUP

Engine Compartment

To accommodate the new engine and generator, a number of modifications were required within the rear engine compartment. A photo of the compartment prior to installation of the new engine is shown in Figure 5–1.

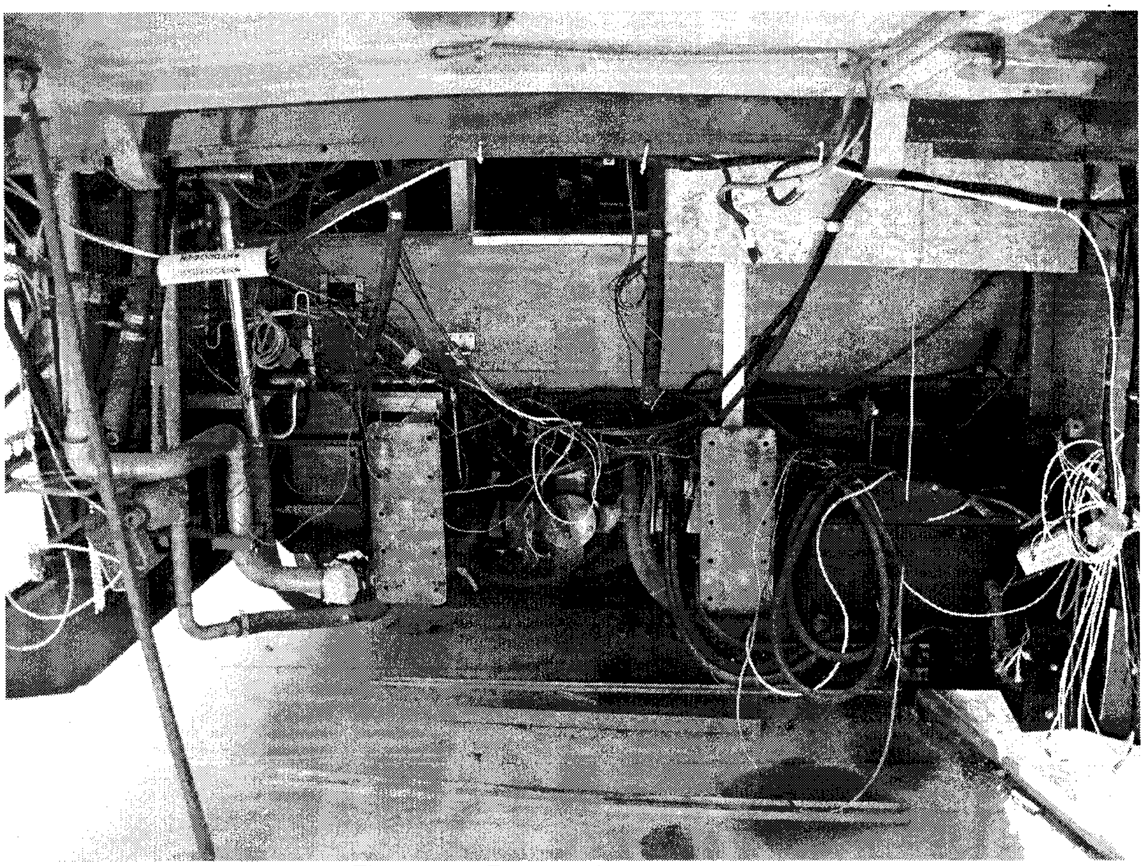


Figure 5–1 Rear engine compartment

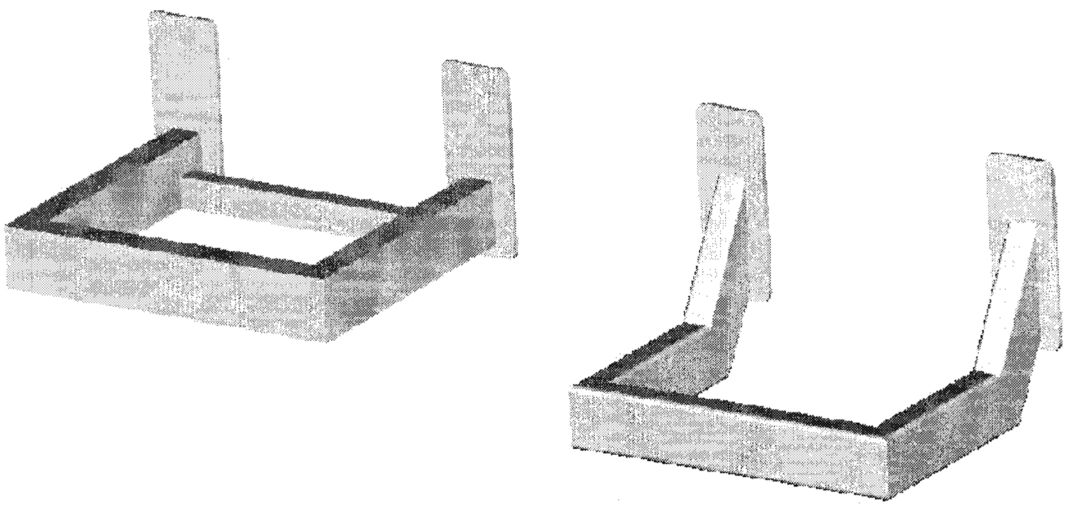


Figure 5–2 Engine cradle comparison (Original is shown on the left)

A significant alteration was made because of the tuned air intake system. Due to the long intake runners, the entire engine/generator assembly needed to be lowered by approximately six inches. Lowering the engine required the alteration of the cradle that mounts to the two rectangular bolt plates seen in Figure 5–1and extends rearward to hold the engine and generator. A comparison between the original (left) and final (right) designs is shown in Figure 5–2.

Another modification that was made to the engine compartment was to create a shelf on which the super-capacitor unit for the regenerative braking system could be located. The rear of this shelf can be seen to the right in Figure 5–1. In addition, a majority of the wiring and much of the plumbing in the engine compartment was either removed or relocated. A final image of the engine compartment with the new hydrogen engine and generator is shown in Figure 5–3.

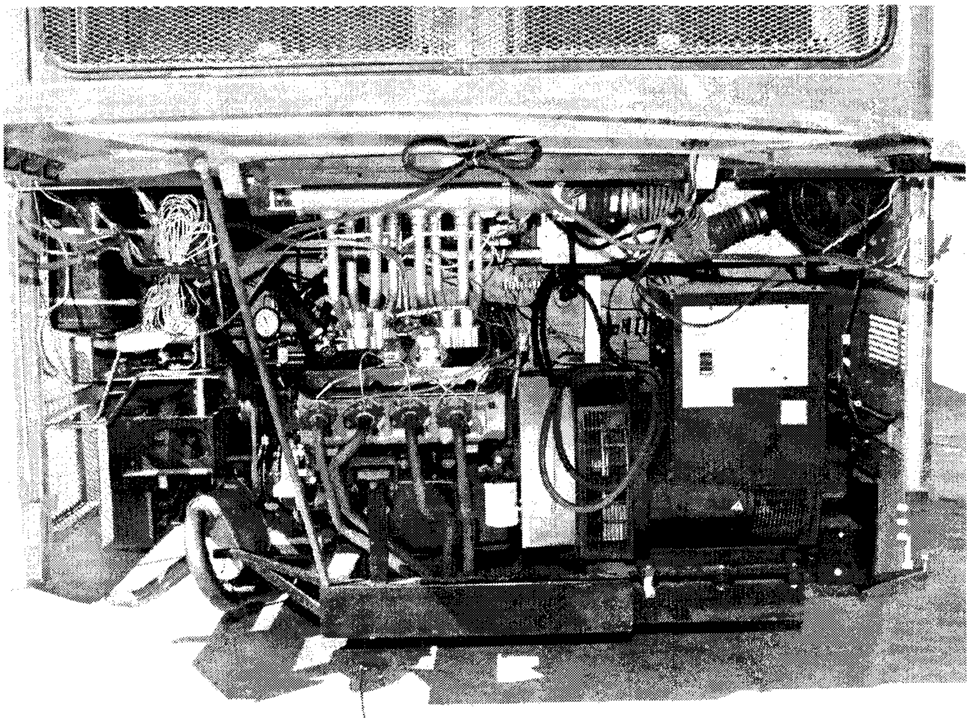


Figure 5–3 H2 engine installed in bus

System Connections

The major connections between the engine and the peripheral systems include water, air, fuel, power and electronic controls.

Water

The cooling system for the hydrogen engine uses automotive antifreeze that is passed through two large radiators in the compartment directly above the engine. The engine coolant is also used to warm the hydride beds. The coolant supply line emerges from the roof in the left side of the engine compartment. The coolant return line is routed forward from the left side of the engine. Both lines attach to the water pump on the engine.

The water injection system utilizes de-ionized water stored in a 5-gallon pressurized reservoir located on the left side of the engine compartment. From the reservoir, a clear plastic line is routed to the water injection solenoid valve located in the center of the air intake plenum.

Air

The air intake system includes a filter located on the far right side of the engine compartment. From the filter, a flexible duct is connected to the throttle body.

Fuel

The hydrogen fuel supply line coming from the hydride beds is labeled as HYDROGEN. The supply line emerging from the front of the engine compartment is passed through a mass flow sensor and a regulator before the connection to the engine. The details of the fuel delivery system can be found in the Fuel Delivery section.

Power

The engine gets its power from a standard heavy duty automotive battery located on the right side of the engine compartment forward of the generator.

Bus Testing

Once the engine and generator was installed in the bus, the bus was taken to the Las Vegas Motor speedway to perform a preliminary operations test to check the functionality of the entire bus. The plan was to purge the hydride storage system of air, fuel the bus and then operate the bus for a while to allow the recharging cycle to complete a couple of times.

The bus was taken to the speedway and the purge was performed. Upon the start of the fueling process, a leak was detected by one of the hydrogen sensors. It was determined that the leak was coming from one of the lines inside the passenger side box that housed the hydride vessel. The refueling was stopped immediately and the system purged of all hydrogen. It was decided by the Bechtel officials not to pursue the repair of the hydride beds because of the cost involved.

In light of the decision not to continue with the bus, there has been a project proposed where the engine would be removed from the bus and put into operation at the City of Las Vegas facility for distributed generation where some long-term operation data could be obtained.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The result of this project is an internal combustion engine that operates very well on hydrogen gas with low emissions. Electronic engine control has proven to be an effective method to operate such an engine, giving the control and adjustability required to optimize engine parameters on the fly. This "on-the-fly" control allows the results of changes to be observed immediately during the operation of the engine. The addition of water injection to this engine allowed it to operate on gaseous hydrogen with comparable power output to when it is operated on natural gas which has a volumetric energy equivalent of about three times that of hydrogen. Of the three methods tried in this project, water injection seemed to be the most effective without sacrificing power for stable operation. The drawbacks with it are attaining the water to be injected, having the water pure enough so that it does not clog the nozzles, and the possibility of contaminating the engine oil with water. The first two of these can be solved by condensing the water from the exhaust of the engine. This is not an entirely easy accomplishment, however it can be done. The latter can be addressed with precise computer control of the water injection system. With precise control, pre-ignition can be eliminated and emissions can be reduced without oil contamination.

Recommendations for Future Work

This Project

Some aspects of this engine need further development for this particular engine to reach full potential. These include further refinement of the governor function and the method in which the water injection is controlled. The speed controller programmed into the ECM, while it does perform satisfactorily, needs to be more robust. Because of the voltage characteristics of a

generator, the load applied on the engine is a function of the RPM of the generator. As a result, when the speed of the generator changes, the load applied on the engine changes. The controller does not respond properly to changes in load quickly enough, which causes continuous oscillation occasionally. The water injection control method should be simplified to the point where the user specifies in the software the mass flow rate of the system and the water to fuel ratio that is desired then let the computer calculate the duty cycle of the control solenoid. The current setup requires the user to estimate the duty cycle to get the desired flow rate. In addition, a differential pressure regulator should be added prior to the solenoid to maintain the flow rate of the system as constant. Currently as manifold pressure changes, the pressure differential across the nozzles changes, this affects the flow rate of the nozzles.

More complete emissions data should also be collected for this engine. When the final data was collected, there was a limited supply of hydrogen on hand so more data at different loads could not be obtained. In addition, the instruments used to collect the data had not been calibrated properly for several months due to the lack of calibration gasses for them. However, it is felt that the numbers are suitable for comparison analysis.

Future Projects

Future hydrogen engine projects should include a definitive study of the effects of the compression ratio on the performance parameters of the engine, specifically on NOx emissions. The literature has widely varying views on this leading to the arbitrary selection of one for this engine. It is suspected that lowering the compression ratio would lead to lower emissions because the peak cylinder pressures would be lowered, however this would also lower efficiency and performance.

Fuel injectors are another area that needs more research. The ones used for this engine are bulky, don't seal properly and need special electronics to make them operate. At the time of their selection, there weren't many options available. For future engines, a thorough search should be performed and the injectors used here should be used if nothing else is available.

The tuned intake is effective in increasing the volumetric efficiency on any internal combustion engine at the targeted RPM range. The drawback to this is when the operating PRM

of the engine is relatively low. The low RPM target results in long intake runners that can be hard to fit in an engine compartment. In addition, if the trouble has been gone through to tune the intake, the exhaust should be tuned also because the exhaust has the possibility of counteracting the effects of the intake. If the engine is to be operated at varying speeds, it can be tuned to the range that occurs most frequently to help with the overall efficiency of the engine.

APPENDIX

Original Hydrogen System Background

In the fall of 1998, the Energy Research Center at the University of Nevada, Las Vegas was supplied by the US Department of Energy with one of the first hydrogen fueled electric hybrid buses from the Savannah River Bus Project. A description of the initial design is given in a paper and the project final report [8,9]. The purpose of this acquisition was to enhance the performance of the bus to make the concept commercially viable. The bus system was expected to have a range of over one hundred miles (161 km), maximum fuel consumption around six kilograms of hydrogen per hour, a top speed of 55 miles per hour (88.5 km/h) and near zero emissions. To accomplish this, the performance of several of the subsystems within the bus needed to be enhanced. The existing design consisted of a conventional electric bus with the addition of a metal hydride storage system for the onboard storage of gaseous hydrogen [10] and an Auxiliary Power Unit (APU). The APU consisted of a Ford LSG-875 industrial multi-fuel 7.5 liter V-8 engine modified to run on gaseous hydrogen coupled with an electric generator to charge the batteries and supply additional power to the electric drive motor.

The area in which the most performance improvements could be realized was with the hydrogen-fueled engine. The necessary power output for the existing Ford engine was established as 70 kilowatts at a speed of 2500 revolutions per minute. RPM limitations were due to the operating range of the generator. Changes that had been made to the engine for the conversion to hydrogen gas included the addition of an HCI Constant Volume Injection system, the addition of exhaust gas recirculation, and modifications to the heads and pistons.

The Constant Volume Injection system was a unique sequential multi-port fuel injection method to meter the flow of hydrogen into each cylinder. The system is based upon the ideal gas relationship between pressure, volume and temperature. Not only do the pressure and volume

affect the flow of gas into the engine, but also changes in temperature can have adverse effects. To combat this, an electronic control system was utilized in this injection arrangement.

The exhaust gas recirculation system was employed primarily to control pre-ignition and secondly, to reduce emissions and utilize any unburned hydrogen. The system drew the exhaust from one side (four of the eight cylinders) of the engine through heat exchangers, into a condenser and then into a mixer at the intake manifold.

The engine heads and pistons had been replaced to increase the compression ratio and hence the thermal efficiency. In an attempt to reduce the excessive amounts of oil lost during operation, new piston rings were installed.

Original System Evaluation

Following the acquisition of the bus, the engine and generator were removed for extensive evaluation. After several weeks of dynamometer testing of the Ford engine, it was determined that there were a number of issues that would need to be addressed to bring the system up to the desired operating specifications.

The most significant problem with the existing engine centered on the fuel delivery system. Using pressure transducers on the input and outputs of the fuel injection system, it was found that the pressure (and therefore the mass) of the fuel delivered to each cylinder varied radically. To remedy this inconsistency, it was determined that the fuel metering system needed to be upgraded.

Additionally, there were a number of concerns related to the exhaust gas recirculation strategy and implementation. Since the system was set up to recirculate all of the exhaust from one half of the engine, the volumetric efficiency of the engine dropped dramatically from an average of 73.3% to 38.3% when the EGR system was used. In addition, the fuel efficiency fell by as much as 20% when the EGR system was used (see Figure A–1). However, The extensive recirculation system was vital to keep the engine under control and keep the emissions low, therefore, it must remain in place on this engine to provide the required performance. The two difficulties outlined above, coupled with other problems such as high oil consumption that was

resulting in high hydrocarbon emissions in the exhaust, led to the eventual decision to redesign the hydrogen engine rather than to attempt to modify the existing one.

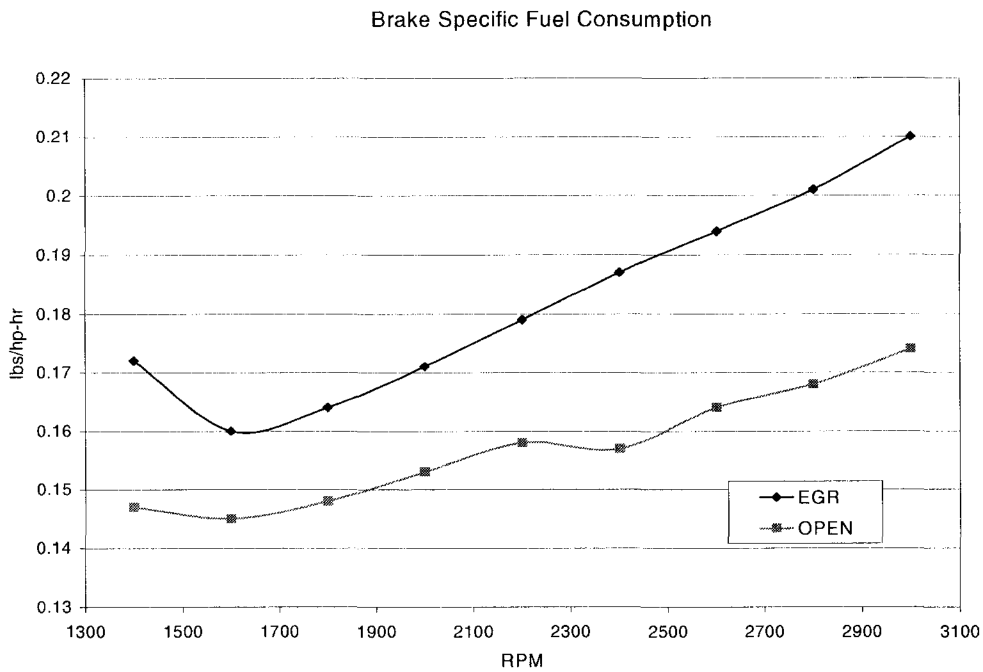


Figure A–1 Fuel efficiency comparison

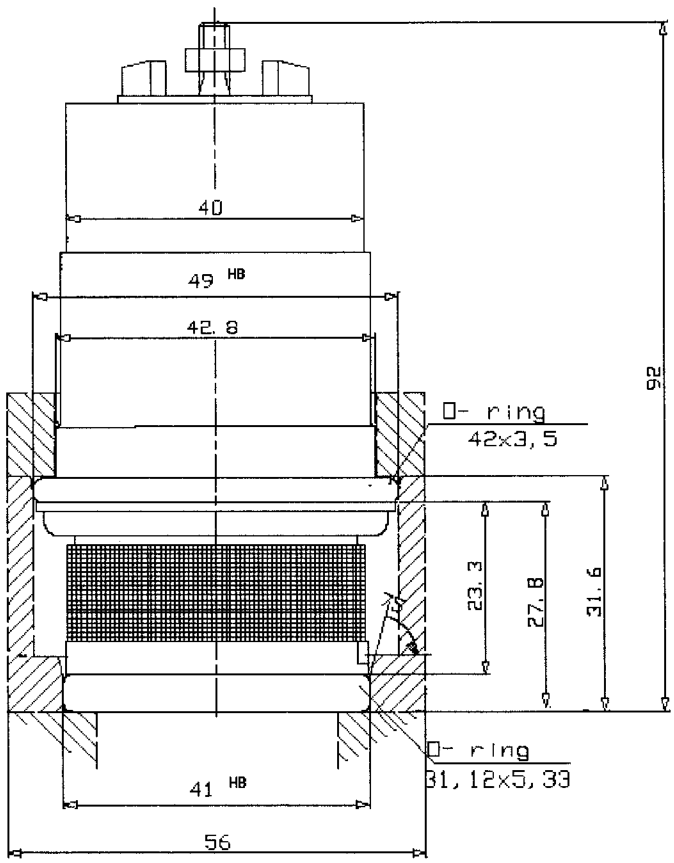
Project Timeline

October 1998	Bus Arrived at the Center for Energy Research in Nevada
May 1999	Engine and Generator removed from bus
June 1999 – August 1999	Engine tested on dynamometer at Kell's Automotive
October 1999 – December 1999	Fuel injector research and design
December 1999 – February 2000	Machining of fuel injector mounts and associated parts
February 2000 – May 2000	Designing custom air intake system Machining custom air intake system
May 2000 – July 2000	Engine Assembly and various custom machining
July 2000	Displayed at ENERGEX 2000 show in Las Vegas, Nevada
August 2000	Engine first run on Natural Gas
September 2000	Engine first run on Hydrogen
September 2000 – November 2000	Enhanced fuel injection driver circuitry Installed initial catalytic converter for testing Experimented with various spark plugs
November 2000 – December 2000	Modified fuel injectors for higher flow capacity
January 2001 – March 2001	Engine dynamometer testing & various modifications
March 2001 – May 2001	Engine coupled to generator and tested using a resistive load Electronic throttle control developed
June 2001 – August 2001	Water injection system design & construction Testing of water injection system
August 2001 – September 2001	Engine mounting design & construction
September 2001 – November 2001	Exhaust header design & construction
January 2002 – June 2002	Systems optimization & repeatability testing
July 2002	Final dynamometer testing of engine
August 2002—September 2002	Installation of engine / generator set and wiring in bus
October 2002	Attempted Testing of new H2Fuel bus at Las Vegas Motor Speedway

HOERBIGER

Hoerbiger Gas Port Injector GV22

Drawing:



HOERBIGER

Data Sheet:

Performance	
Equivalent flow area (adjustable)	9.0 - 16.0 mm^2
Steady state flow rate at reference conditions	5.5 - 10.2 g/s
Maximum pressure difference across valve	4.5 bar
maximum allowable inlet pressure	10 bar
Valve response time	1 ms
Max. variation in opening and closing time	20 % of actual value
Max. variation in effective flow area	+/-5 %
Max. leakage in % of full flow	0.2 %
Supply voltage	24 - 48 V
Pull-In current	8 A
Hold-In current	3.5 A
Resistance	0.25 Ω
Typical Power consumption (full load 2200 rpm)	2 W
Interfaces	
Gas inlet	radial
Valve diameter	49 mm
Valve height	92 mm
Fuel gas properties	
Max. particle size	5 μm
Max. particle concentration	1 ppm
no condensing moisture	
Reference Conditions	
Wobbe Index of fuel gas	49.5 MJ/mn^3
i.e. gas density	0.808 kg/mn^3
caloric value	39.2 MJ/mn^3
Gas inlet pressure	4 bar
Receiver pressure	3 bar

Markus Digruber
Hoerbiger Ventilwerke GmbH
Austria

Solenoid and driving data for operating the Hoerbiger gas admission valve GV22:

DATA SHEET

Voltage supply	24 - 48	V	
Electrical resistance (approx.)	0.25	Ω	
Pull-in-current	8	A	± 10%
Hold-in-current	3.5	A	± 10%
Valve response time	1	ms	
Typical power consumption	2.1	W	

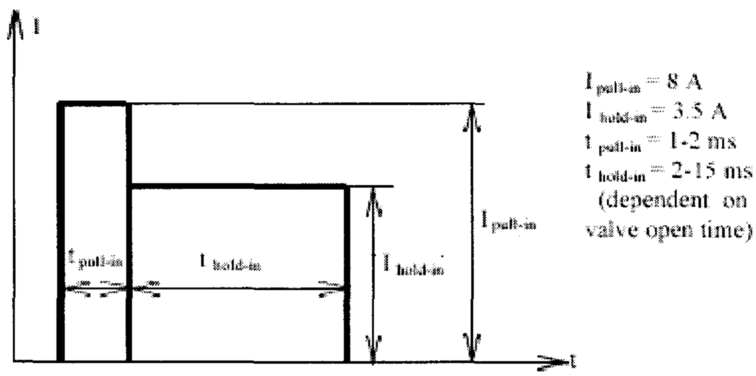
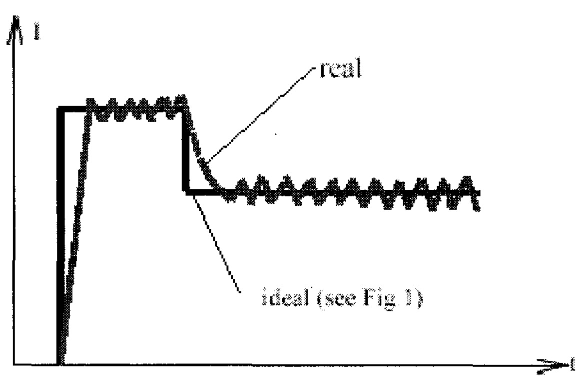


Fig. 1: Typical values for pull-in and hold-in current, and pull-in and hold-in time.



Test Data

Filename:	DATE	TIME	Increment	TEST #	Lt. F. JET	Rt. F. JET	Lt. R. JET	Rt. R. JET	TIMING
H2July17 .Dy1	07/17/02	15:11:40	100	1	0	0	0	0	0

RPM	TORQUE	HP	C. FACT	C. TQ	C. HP	BMEP	BSFC	BSAC	ACFM	# AIR	# FUEL	A/F	VE%	TE%
1700	287.60	93.09	1.1073	318.46	103.08	94.2	0.169	5.833	134.1	543.0	15.72	34.54	59.3	29.2%
1800	295.75	101.36	1.1079	327.65	112.29	96.9	0.161	6.286	157.5	637.1	16.33	39.03	65.6	30.7%
1900	296.85	107.39	1.1080	328.91	118.99	97.2	0.157	6.148	163.2	660.2	16.90	39.06	64.5	31.4%
2000	306.01	116.53	1.1098	339.59	129.32	100.2	0.156	6.094	175.9	710.1	18.19	39.05	66.1	31.7%
2100	313.51	125.36	1.1102	348.07	139.17	102.7	0.158	6.228	193.5	780.8	19.76	39.50	69.2	31.3%
2200	313.24	131.21	1.1097	347.61	145.61	102.6	0.158	6.173	200.7	810.0	20.67	39.19	68.5	31.3%
2300	313.10	137.12	1.1096	347.43	152.15	102.6	0.162	6.129	208.2	840.4	22.19	37.87	67.9	30.5%
0	0.00	0.00	0.0000	0.00	0.00	0.0	0.000	0.000	0.0	0.0	0.00	0.00	0.0	
0	0.00	0.00	0.0000	0.00	0.00	0.0	0.000	0.000	0.0	0.0	0.00	0.00	0.0	
0	0.00	0.00	0.0000	0.00	0.00	0.0	0.000	0.000	0.0	0.0	0.00	0.00	0.0	

RPM	#1	#2	#3	#4	#5	#6	#7	#8	AVER.	DIFF.	BARO	R. H.	V. P.	C. BARO	AIR F
1700	1080	1064	1018	1102	1004	1138	1037	1016	1057.4	134	28.12	0.38	0.46	27.66	84
1800	1061	1028	1025	1075	1031	1122	1054	1035	1053.9	97	28.12	0.38	0.47	27.65	84
1900	1073	1051	1071	1084	1065	1138	1103	1093	1084.8	87	28.11	0.38	0.46	27.65	84
2000	1085	1051	1070	1084	1072	1139	1104	1102	1088.4	88	28.10	0.38	0.48	27.63	85
2100	1146	1118	1108	1133	1121	1210	1134	1144	1139.2	102	28.10	0.38	0.48	27.62	85
2200	1138	1094	1100	1107	1106	1188	1129	1137	1124.9	94	28.09	0.37	0.46	27.63	85
2300	1176	1167	1134	1149	1145	1265	1161	1159	1169.5	131	28.09	0.37	0.46	27.63	85
0	0	0	0	0	0	0	0	0	0.0	0	0.00	0.00	0.00	0.00	0
0	0	0	0	0	0	0	0	0	0.0	0	0.00	0.00	0.00	0.00	0
0	0	0	0	0	0	0	0	0	0.0	0	0.00	0.00	0.00	0.00	0

Table A—1 Final data set

Filename:	DATE	TIME	Increment	TEST #	Lt. F. JET	Rt. F. JET	Lt. R. JET	Rt. R. JET	TIMING
H2fullthrottle new catalyst.dy1	03/15/01	14:35:49	100	1	0	0	0	0	0

RPM	TORQUE	HP	C. FACT	C. TQ	C. HP	BMEP	BSFC	BSAC	ACFM	# AIR	# FUEL	A/F	VE%	TE%
1800	332.14	113.83	1.0883	361.45	123.88	108.8	0.166	5.589	153.0	636.3	18.84	33.77	63.8	29.8%
1900	333.24	120.56	1.0896	363.11	131.36	109.1	0.167	6.508	189.1	784.6	20.13	38.97	74.6	29.6%
2000	333.62	127.04	1.0899	363.61	138.46	109.3	0.166	6.420	196.6	815.6	21.10	38.65	73.9	29.7%
2100	338.63	135.40	1.0908	369.38	147.69	110.9	0.166	5.875	192.1	795.5	22.54	35.29	68.7	29.7%
2200	338.78	141.91	1.0909	369.56	154.80	111.0	0.169	5.855	200.7	830.9	23.98	34.65	68.3	29.2%
0	0.00	0.00	0.0000	0.00	0.00	0.0	0.000	0.000	0.0	0.0	0.00	0.00	0.0	
0	0.00	0.00	0.0000	0.00	0.00	0.0	0.000	0.000	0.0	0.0	0.00	0.00	0.0	
0	0.00	0.00	0.0000	0.00	0.00	0.0	0.000	0.000	0.0	0.0	0.00	0.00	0.0	
0	0.00	0.00	0.0000	0.00	0.00	0.0	0.000	0.000	0.0	0.0	0.00	0.00	0.0	
0	0.00	0.00	0.0000	0.00	0.00	0.0	0.000	0.000	0.0	0.0	0.00	0.00	0.0	

RPM	#1	#2	#3	#4	#5	#6	#7	#8	AVER.	DIFF.	BARO	R. H.	V. P.	C. BARO	AIR F
1800	347	340	328	339	339	384	328	356	345.1	56	27.99	0.11	0.10	27.89	74
1900	350	343	331	341	342	387	331	359	348.0	56	27.98	0.11	0.10	27.88	75
2000	357	348	337	346	348	392	337	364	353.6	55	27.97	0.11	0.10	27.87	75
2100	360	351	340	349	351	395	339	366	356.4	56	27.97	0.10	0.10	27.88	76
2200	363	354	342	351	353	397	342	367	358.6	55	27.96	0.10	0.09	27.87	76
0	0	0	0	0	0	0	0	0	0.0	0	0.00	0.00	0.00	0.00	0
0	0	0	0	0	0	0	0	0	0.0	0	0.00	0.00	0.00	0.00	0
0	0	0	0	0	0	0	0	0	0.0	0	0.00	0.00	0.00	0.00	0
0	0	0	0	0	0	0	0	0	0.0	0	0.00	0.00	0.00	0.00	0
0	0	0	0	0	0	0	0	0	0.0	0	0.00	0.00	0.00	0.00	0

Table A—2 Preliminary data set

Filename:	DATE	TIME	Increment	TEST #	Lt. F. JET	Rt. F. JET	Lt. R. JET	Rt. R. JET	TIMING
H2constant 1800.Dy1	02/19/01	9:45:36	0	1	0	0	0	0	0

RPM	TORQUE	HP	C. FACT	C. TQ	C. HP	BMEP	BSFC	BSAC	ACFM	# AIR	# FUEL	A/F	VE%	NOx Pre	NOx Post
1800	285.27	97.77	1.0826	308.84	105.85	93.4	0.173	5.521	128.3	539.8	16.93	31.89	53.7		26
1800	242.60	83.15	1.0822	262.55	89.98	79.5	0.177	5.873	116.1	488.3	14.75	33.11	48.5		15
1800	229.10	78.52	1.0840	248.33	85.11	75.0	0.187	5.866	109.8	460.6	14.66	31.41	45.7	3180.0	19
1800	203.88	69.88	1.0839	220.99	75.74	66.8	0.192	6.048	100.8	422.6	13.45	31.43	41.8	3050.0	10
1800	170.89	58.57	1.0838	185.21	63.48	56.0	0.210	6.249	87.3	366.0	12.27	29.83	36.5	2790.0	6
1800	146.21	50.11	1.0849	158.63	54.37	47.9	0.220	6.594	78.9	330.4	11.02	30.00	32.9	2550.0	6
1800	120.43	41.28	1.0841	130.56	44.75	39.4	0.238	6.937	68.3	286.3	9.84	29.10	28.5	2360.0	3
1800	99.00	33.93	1.0837	107.29	36.77	32.4	0.257	7.314	59.2	248.2	8.71	28.50	24.7	2000.0	2
0	0.00	0.00	0.0000	0.00	0.00	0.0	0.000	0.000	0.0	0.0	0.00	0.00	0.0	0.0	0
0	0.00	0.00	0.0000	0.00	0.00	0.0	0.000	0.000	0.0	0.0	0.00	0.00	0.0	0.0	0

RPM	#1	#2	#3	#4	#5	#6	#7	#8	AVER.	DIFF.	BARO	R. H.	V. P.	C. BARO	AIR F
1800	278	274	263	273	272	307	264	286	277.1	44	28.08	0.33	0.23	27.85	67
1800	312	306	295	303	308	341	298	316	309.9	46	28.09	0.29	0.21	27.89	68
1800	320	314	303	311	315	351	306	326	318.2	48	28.09	0.30	0.22	27.87	69
1800	328	322	310	319	323	360	313	334	326.1	50	28.09	0.30	0.22	27.87	69
1800	332	326	314	323	327	364	316	338	330.0	50	28.09	0.30	0.22	27.87	69
1800	340	329	321	326	330	368	319	341	334.2	49	28.10	0.30	0.23	27.87	70
1800	343	332	323	329	332	370	322	343	336.8	48	28.11	0.29	0.22	27.89	70
1800	342	332	323	329	332	370	321	343	336.5	49	28.12	0.28	0.22	27.90	70
0	0	0	0	0	0	0	0	0	0.0	0	0.00	0.00	0.00	0.00	0
0	0	0	0	0	0	0	0	0	0.0	0	0.00	0.00	0.00	0.00	0

Table A—3 Some early performance and emissions numbers

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