# Development of a Hydrogen Powered HEV as an Interdisciplinary Laboratory Project

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## I Introduction

Over the past several years, Texas Tech University's Advanced Vehicle Engineering Laboratory (AVEL) has converted six conventional vehicles to hybrid electric (HEVs) and alternative fueled vehicles for the various Vehicle Challenges sponsored by the U.S. Department of Energy (DOE), the three major U.S. automobile manufacturers, the Society of Automotive Engineers and Natural Resources Canada.

Of particular interest today is the popularity of full sized sport utility vehicles (SUV). These vehicles are reversing the trends, over the last few years, of reduced emissions and improved fuel economy. In line with these problems, Texas Tech University is developing a hybrid Ford Explorer powered by 2.3 liter spark ignition engine, running on hydrogen, in parallel hybrid configuration with a 75 kilowatt induction motor. Two nickel metal hydride battery packs connected in parallel at 300 Volts DC nominal provide 13 Amp hours to drive the electric motor. The hybrid design maximizes efficiency with electric assistance adding to the vehicle's performance during high engine loads and maintains a self sustaining charge through regeneration at times of low power train demands. A National Instruments' LabVIEW system is used to monitor and control the vehicle.

The development of the vehicle is a multidisciplinary project with students from mechanical engineering, electrical engineering and computer science involved. The majority of the undergraduate team members are enrolled in a two-semester senior design sequence. However, graduate students and volunteers also participated in the program. Faculty advisors from both electrical and mechanical engineering provide guidance for the team. Large, interdisciplinary team projects like this can give students a more complete understanding of interfacing, decision making and cooperation.

## II. Hydrogen as a Fuel

Hydrogen has been referred to as the ultimate fuel. It is the most plentiful element in the universe. On a basis of carbon atoms per fuel molecule, it is at the cleanest end of the fuel spectrum. This makes hydrogen the fuel of most promise because it has the potential of producing only water when reacted with the oxygen from air. [1]

The primary motivation for using hydrogen as an energy carrier is that it provides a means of managing carbon dioxide emissions. Converting the end-use technologies to hydrogen allows the consumption of hydrocarbon fuels with large-scale carbon management schemes in place at the point of hydrogen production. In addition, once the supply infrastructure and end-use technologies for using hydrogen are in place, then the evolution towards hydrogen production from renewable energy resources becomes transparent to the user. [2]

The major driving force of internal combustion engine technology development during the last three decades has been the environment. Industry is facing zero regulated emissions as well as substantial reductions in $CO_2$ emissions. Although hydrogen fueled fuel cells are being considered as a promising candidate for the future, there are two significant issues preventing this development. First, there is no infrastructure for the hydrogen as a readily available fuel. Second, high volume production feasibility of fuel cells has not been achieved due to high cost and reliability issues. [3]

A hydrogen powered internal combustion engine (H2ICE) is a possible simple and inexpensive interim solution utilizing the existing capital investment and technology of the automotive industry. H2ICEs could stimulate the fuel distribution infrastructure in an efficient manner, provide quick response to environmental and market demands and provide a stepping-stone to the ultimate introduction of the fuel cell. [3]

An additional problem for current vehicles is fuel economy. The concept of fuel economy or fuel savings is linked to the problem of non-renewable fossil fuels. The use of hydrogen as a fuel can theoretically provide infinite “fossil fuel” economy.

## III. Power Train

The Texas Tech University H2ICE-HEV vehicle component layout is shown in Figure 1. A Ford 2.3liter, 170hp at 5500rpm, four-cylinder engine is the main power source. This engine was chosen because of the availability of parts and aftermarket accessories. The engine was rebuilt and cleaned thoroughly to remove any carbon deposits that could heat up and cause preignition. Since hydrogen can support higher compression ratios and boost without detonation, the standard dished pistons were replaced with flat top ones and heads with smaller combustion chambers were installed, resulting in about 12:1 compression ratio. Cylinder head material also plays a key role in a hydrogen engine. Pre-ignition can be a major problem and thus cooling the combustion chamber is a major concern. For this reason, Esslinger aluminum cylinder heads were installed.

The fuel delivery system was changed, including everything from the tanks to the fuel rails and injectors. The hydrogen fuel injectors were direct replacements for regular gasoline injectors. A fuel rail, however, was not available, and a custom made stainless steel one was fabricated. The complete fuel system is shown in Figure 2.

Two tanks, connected effectively in parallel, store hydrogen to fuel the vehicle. Each tank is approximately 19.1” in diameter and 29” (not including regulator) long. Each tank can hold a maximum operating pressure of 5000 psi. The two tanks are located in the rear cargo area. The tank bracket is welded directly to the vehicle frame.

The transmission is a four speed automatic transmission which was originally mounted to the engine. The transmission is easy to control, and only requires an electronic input to the lock-up torque converter. The overdrive gear provides good fuel economy and reduced engine noise.

The TTU H2ICE-HEV uses a post-transmission power train configuration. The internal combustion engine delivers power to the automatic transmission which turns a drive shaft. This drive shaft delivers power to an electric motor that was modified to have shafts coming from both ends. The motor then has a short drive shaft connecting to the rear differential. Essentially this set up replaces a piece of the drive shaft with the electric motor.

The electric motor is a Solectria AC55 with 75kW peak and 35 kW continuous power. Two battery packs are used for the electric drive train and are mounted one on either side of the drive shaft. The battery packs are Toyota Prius nickel metal hydride (NiMH) packs with a 273 VDC nominal voltage and 13 AHrs capacity. The batteries are housed in separate lexan boxes with built-in ventilation.

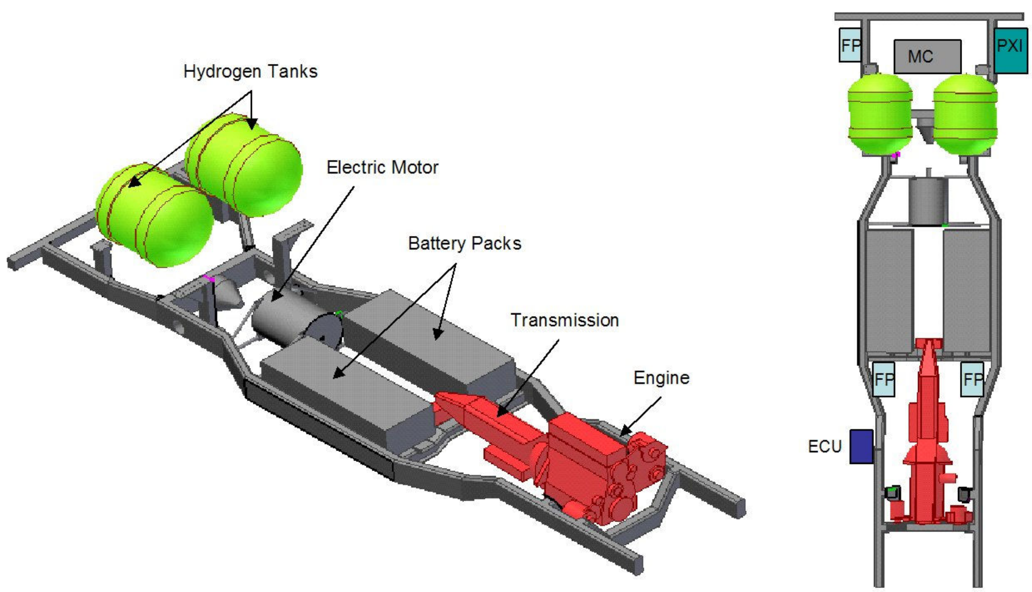


Figure 1: Component Layout

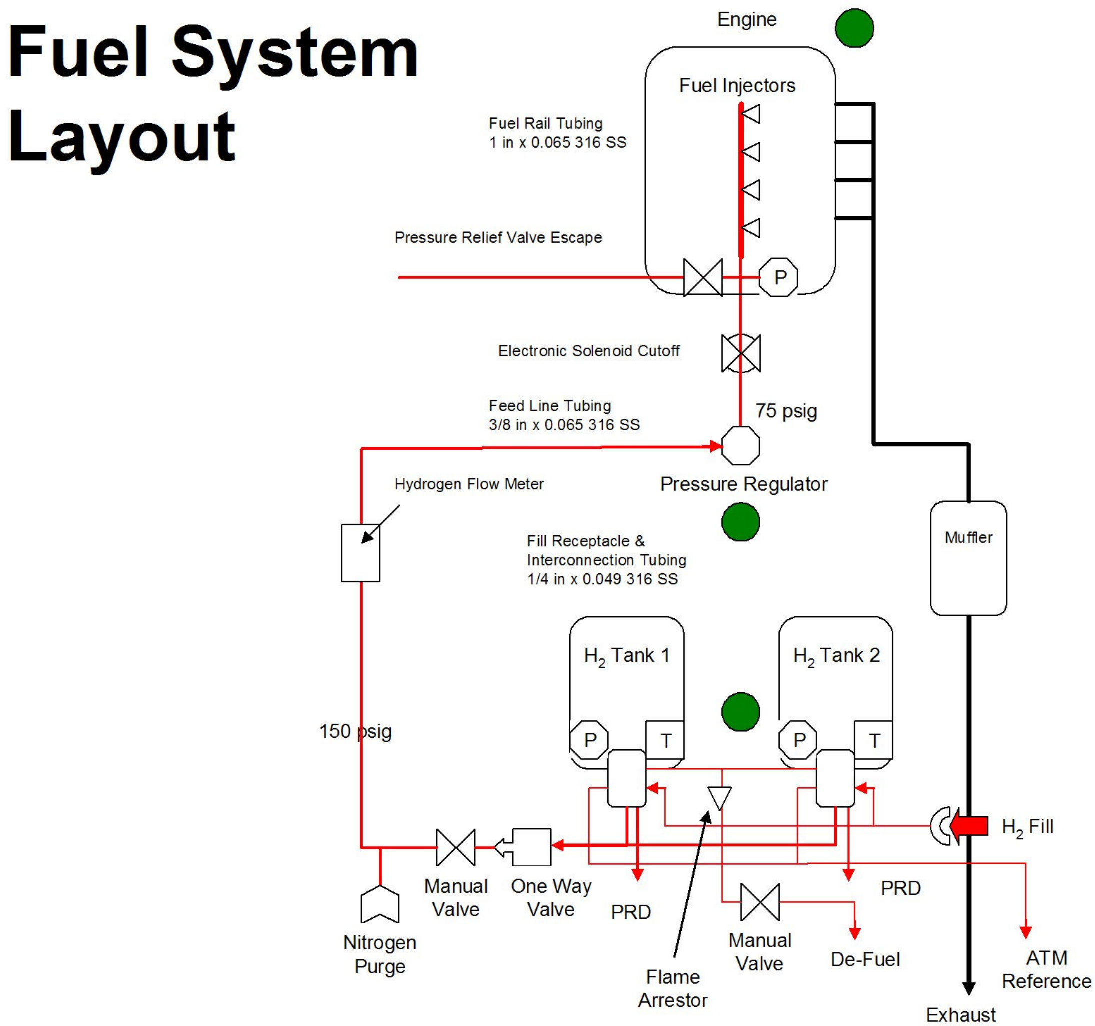


Figure 2. Fuel System

IV. Engine Control

The engine control unit (ECU) is a Motec M4. This ECU was chosen because it has specific control over the three major engine parameters: fuel injection amount, fuel injection timing, and ignition timing. These three parameters are controlled by the engine feedback variables rpm, load, and equivalence ratio. Hydrogen engine control parameters are based primarily on avoiding pre-ignition and back-flash.

The Motec M4 was also chosen for its sequential injection and sequential ignition capabilities on a four-cylinder engine. Other important features of the Motec M4 include on board internal data logging and external data acquisition. Internal data logging allows for logging of the ECU sensors and engine parameters for up to six hours. External data acquisition uses National Instruments PXI instrumentation system, in which the electric assist algorithm is executed.

For sequential ignition and sequential injection to run correctly cam shaft (sync) and crank shaft (ref) sensors must be added to the engine so that the ECU knows exactly each position of all four cylinders. Sequential ignition is preferred so that there is not a wasted spark on the exhaust stroke which could lead to a back fire of unburned hydrogen. Sequential injection is done using port fuel injection (PFI); that is, fuel is injected one cylinder at a time only when the intake valve is open. On electronic injected gasoline engines, fuel is injected in groups at one time, where the gasoline, which is heavier than air, waits for the intake valve to open. Hydrogen on the other hand is lighter than air and does not sit and wait for the intake valve to open, but rises and disperses in the intake manifold. So, with PFI hydrogen will only be injected when the intake valve is open so that the vacuum pulls the hydrogen directly into the combustion chamber.[4]

The major input that affects the fuel injection is the lambda sensor that measures the oxygen content in the exhaust manifold. Lambda is a measurement of the actual air fuel ratio divide by the stoichiometric air fuel ratio. The inverse of lambda is known as the equivalence ratio another useful parameter measuring fuel air ratios. The stoichiometric air fuel ratio for hydrogen is 34.2:1.[5] Hydrogen engines frequently run extremely lean at 0.5 to 0.7 equivalence ratio which results in an air fuel ratio about 62:1. One of the main reasons for running the engine at such lean mixtures is to reduce the tendencies of pre-ignition, which is the ignition of hydrogen inside the combustion chamber due to hot spots before the ignition spark. Another reason for running such a lean mixture is to reduce the amount of NOx emission so that the vehicle can meet low emission vehicle standards. The lambda sensor is monitored by the ECU so that the fuel injected maintains a lean fuel air equivalence ratio. The desired equivalence ratio ranges between 0.5-0.7 to keep NOx emissions to a minimum. NOx emissions verses equivalence ratio can be seen in Figure 11. An equivalence ratio of one can be run at cranking and up to 2000rpm. At these low engine speeds there is enough time to push the required amount of air to reach a stoichiometric equivalence ratio, but as the engine speed increases there is less time to induct air into the cylinder. With less air there is more fuel which causes a higher probability of pre-ignition. At higher engine speed the equivalence ratio is run lean to accommodate the time and amount of air in the cylinder and also avoid the peak NOx emissions.

An example of the output of the ECU running the H2ICE is shown in Figure 3.

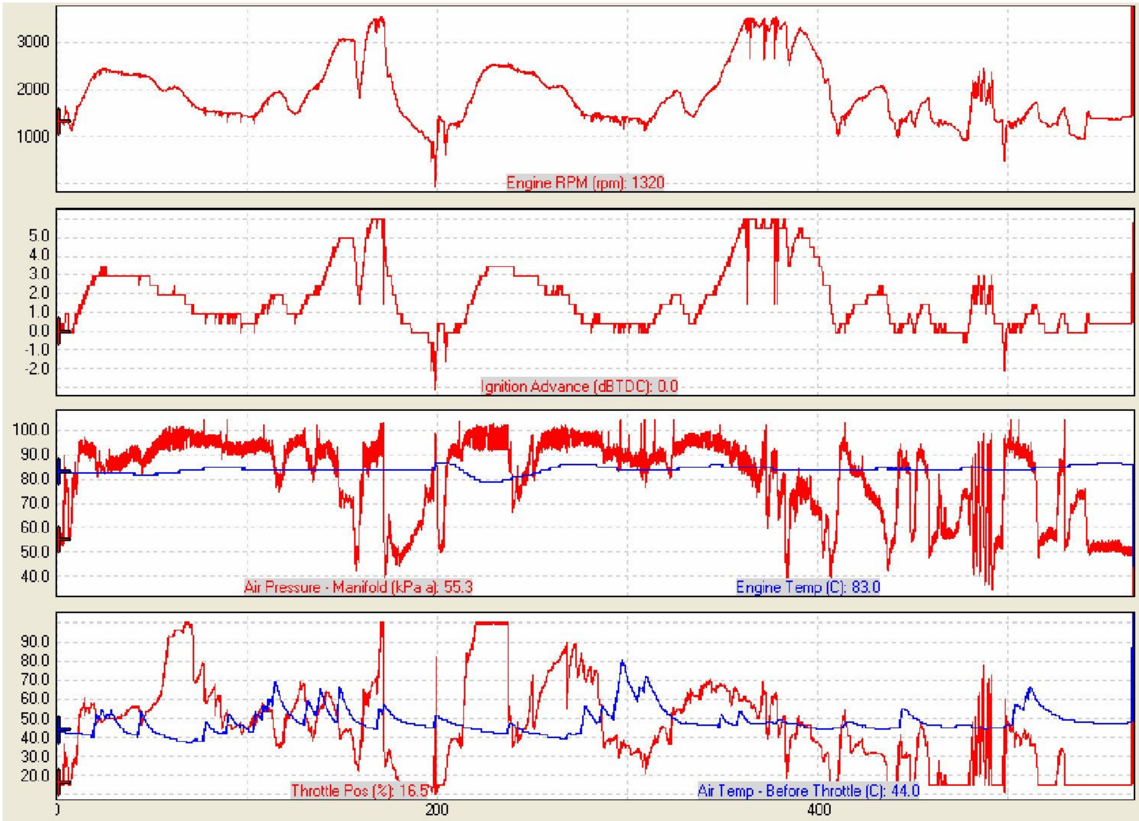


Figure 3. Sample ECU Output

V. Vehicle Control

The vehicle is designed to operate under a single mode of operation to meet the needs of all engine loads and maintain a self sustaining charge. The electric motor is engaged when driving conditions require additional assistance without driver input deviating from traditional control of the throttle pedal, column shifter, and brake pedal. Engine load and vehicle speed are taken into consideration to determine the amount of electrical assistance required to meet driver demands. Based on these parameters, the electric motor aids in a normal mode of operation during periods of low speeds, high torque demands, or to regenerate energy back into the batteries.

Engine loads are detected from the manifold absolute pressure (MAP) sensor to determine the amount of assistance required from the electric motors. The throttle position sensor provides driver demand input and can be used to project instantaneous driving conditions. These two sensor inputs provide a relation for electric assistance that is directly proportional to engine load and immediate demand.

The control system utilizes National Instruments hardware and software. Each battery is monitored by a four panel compact FieldPoint unit consisting of four cFP-AI-102 modules, four pigtail cables, and a cFP-2000 controller. The cFP-2020 is coupled with an eight panel compact

FieldPoint unit and associated with one digital output, one analog output, and six analog input modules to manage motor controller signals, engine information, dash display, transmission output, battery I/O values, and fuel system. The PXI chassis, controller, multifunction PXI card, and PXI accessories act as a central server for datasocket connections and save data from all devices. The PXI system also handles additional dash display signals and all digital inputs. The PCI-6071E, cable, and connector block are being used to control and monitor engine performance on the dynamometer. Communication is maintained between all devices with the aid of Cisco's Darkstar 1.3 mobile router. Along with the equipment, LabVIEW 6.1 RT is used in a flexible virtual instrument environment. The control system components are shown in Figure 4 and the front panel display of the LabVIEW control is shown in Figure 5.

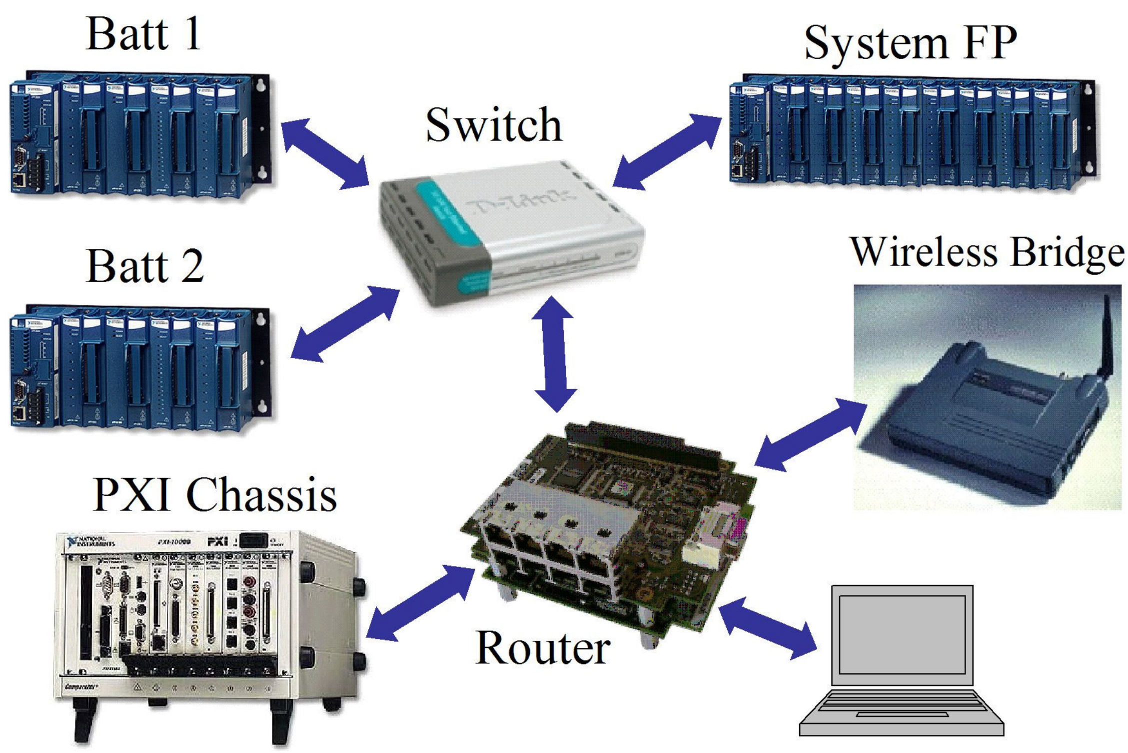


Figure 5. Control System Components

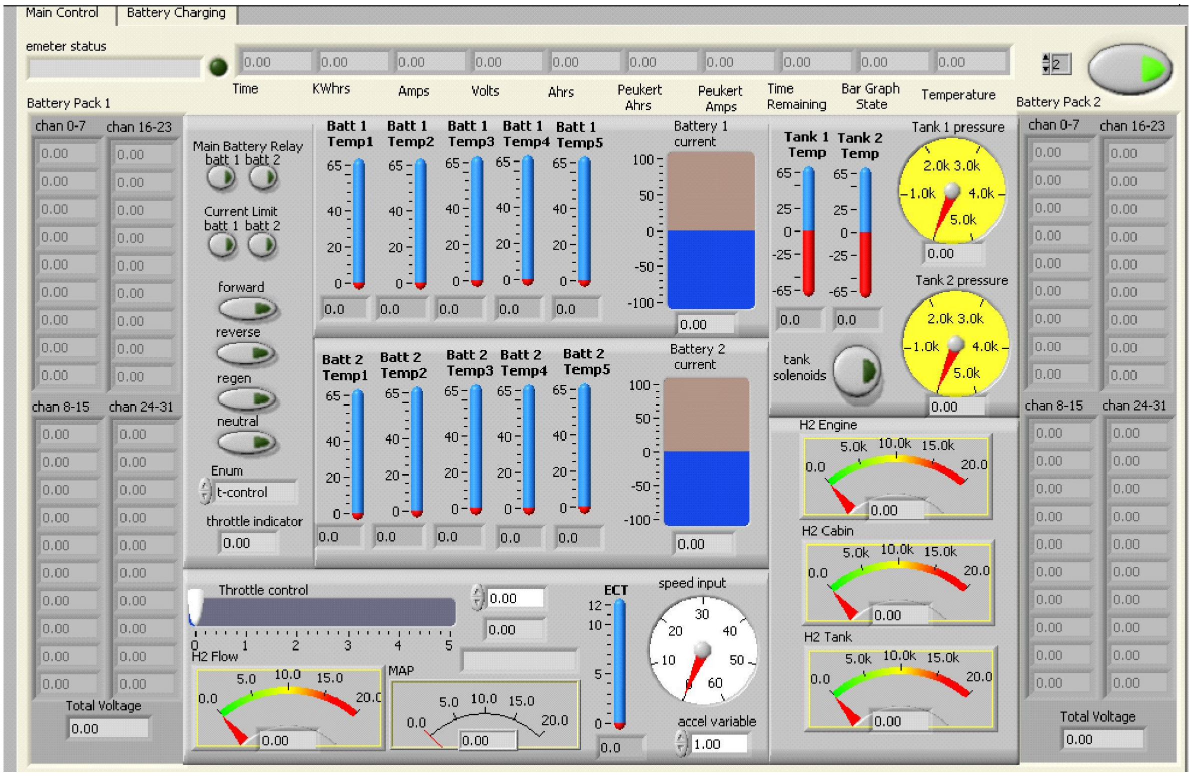


Figure 6. Control System Front Panel Display

## VI. Vehicle Safety

When designing for Future Truck 2003, safety was one of the main concerns. The three systems which pose the greatest safety concerns are the hydrogen fuel system, high voltage system, and the battery packs.

The fuel used in the vehicle is gaseous, compressed hydrogen, which diffuses rapidly and seeks the highest collection point. Hydrogen sensors are strategically placed in multiple collection points on the vehicle to show any indicate of leaks. To ensure the safety of the passengers, the computer initiates an emergency shutdown immediately when hydrogen is detected.
The hydrogen tanks are constructed with an elaborate pressure regulation manifold, in which the output regulation is done in two stages. The first stage regulation reduces the pressure to ~500 psig, and then the second and final regulation brings the pressure to 150 psig. There is a vent used for an atmospheric pressure reference during the second stage of regulation. A solenoid valve low pressure lock off included in the manifold allows for complete isolation of hydrogen within the tanks. There is also a manual override provided that forces the solenoid to an open state. The override is used for de-fueling during the case of a power failure and or emergencies. A thermal relief device is activated if the temperature surrounding the tanks reaches 145°C.

The high voltage system can be isolated from the battery packs by two methods; the emergency disconnect switch (EDS) or the manual isolation switch. The EDS is to be used in case of emergency or to de-energize the vehicle when it is not in use to minimize the expose to high voltage. The purpose of the MIS is to lock out the high voltage system in a complete fail-safe manner while any sort of service is preformed on the vehicle.

## VII. Engineering Team

As is apparent from the preceding discussion this is a large, complex project encompassing many different disciplines. The team was divided into basic areas, similar to the ones listed above. One or more graduate students were assigned to each main area with a number of undergraduate students working with them. The number of students and the particular students working on the project varied semester by semester. The graduate students helped provide continuity for the project. At any one time there were between 15 and 20 students working on the project. All of the team met together at least once a week to discuss progress and problems. An overall Gantt chart was used to track the time line for all aspects of the project. Each team member described what they were doing and the progress of their part of the project. Students have to occasionally change what they are doing to help out on another part of the project. Whoever is available helps. As a result EE students may help to pull engines and ME students may help to wire controllers. We constantly stress to the students that they need to do whatever needs to be done. The students learn to work together, since it is impossible to do the work alone. They learn the importance of documentation, since anyone may be working in any area at anytime.

The project fits within the frame work of the senior undergraduate laboratories in both electrical and mechanical engineering. The undergraduate students make presentations and write reports on the project for their respective classes.

## VIII. Conclusion

The Electrical and Mechanical Engineering Departments at Texas Tech University utilize the development of advanced vehicles to enrich the learning experience for undergraduate and graduate students. We feel the strong team involvement and true interdisciplinary nature is very important to development of students into practicing engineers.

Comments from the students after the project include that they have a much greater appreciation for team work; that there are no EE’s or ME’s we are all just Engineers; and that they had a great time.

## Acknowledgments

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