

IPRO 304 Fall 2004

hybrid fuel cell people transporter



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Executive Summary

This report is a summary of what the team has accomplished over the semester. Overall the team was able to create an improved working system that allowed a wheel chair to run off lithium-ion batteries and to charge the batteries using the fuel cell output and a charging circuit. The charging circuit was created in cooperation with one of our sponsors, MicroSun Technologies LLC.. In addition part of the team performed in-depth research on the possibilities and limitations of a hydrogen economy.

Since the project plan was created at the beginning of the semester on the 10th of September 2004 the objectives and the organization of the teams had to be slightly altered to improve the efficiency and to account for setbacks that occurred during the project.

This project is a continuation of the work done by a previous team. The greatest initial challenge of this project was to get an overview of previous work. It was known that the previous team had performed a few important tests on the fuel cell and their system to operate the wheel chair, but finding all the earlier data was problematic and time consuming. In particular, there was no comprehensive report that summarized all the important tests on a technical basis.

We initially adopted the plans from the previous team, including a 100 mile drive that would be performed a few weeks into the semester. The ultimate goal of this project was to create a hybrid system that would allow the wheel chair to drive from Chicago to Wisconsin. After looking into the legal and safety requirements for the drive it was found that it would not be possible to perform the drive on public roadways. The team was therefore forced to plan the 100 mile drive on campus.

As the system that was initially provided wasn't a hybrid system, we decided to create a hybrid system. The first step in creating a hybrid system was to design a charging circuit that would allow the batteries to be charged from the fuel cell output and by manually changing a switch then allow the same batteries to power the motor. Such a system was hastily designed to meet the deadline for the 100 mile drive set by one of the sponsors. In order to test the designed circuit an extended test drive was to be performed using the system. Sadly two attempts failed partly due to design flaws and partly due to difficulties starting the fuel cell.

Much was learned from the two failed test drives, they not only provided a better understanding of what the actual challenges were for our project, but also showed that the current charging circuit would not function properly with the varying fuel cell output.

It soon became clear that the organization of the teams and the ultimate goals of this project had to be revised as the difficulties in designing a charging circuit were

larger than anticipated at the beginning of the project. Initially it was planned to perform a 100 mile drive using a hybrid system at the beginning of the semester. This plan had to be changed to perform a 100 mile drive at the end of the semester using a working charging circuit and create a theoretical design of a working hybrid circuit that would incorporate the charging circuit design.

Along with the hybridization circuit and charging circuit, research was being performed on the lithium-ion batteries. These batteries provide the power to the motor of the wheel chair and have been specifically designed to fit the needs of the motor. Currently these batteries consist of 24 lithium-ion cells each with 4 in series and 6 in parallel. As lithium-ion cells have the potential of over heating and exploding it is important to find a functioning cooling system. Apart from modifying the batteries to fulfill the requirements set by the charging circuit, this team looked into improving the passive cooling system that is currently being used. Currently the cells are imbedded in aluminum foam and a phase change material (paraffin wax) ensures that the cells do not overheat. As the aluminum foam is expensive and heavy research and thermal testing was performed on the use of carbon instead of aluminum. At the end of the project various thermal tests were performed on the carbon block design to determine the feasibility and the optimal solution but as research still needs to be performed on the blocks no finished product was created.

Apart from the electrical and mechanical engineering challenges to this project, considerable work was carried out in the analysis of a possible hydrogen economy.

First, the safety of using hydrogen was compared to that of gasoline. While there is considerable public concern about using hydrogen, the evidence is ambiguous as to whether hydrogen is more of a safety risk than gasoline. For example, the potential damage from a hydrogen explosion is considerably less than for gasoline, and under some circumstances it is harder to ignite hydrogen.

Second, the economics of hydrogen production, storage, and delivery were reviewed. Hydrogen production costs are roughly twice that of natural gas on the same energy basis. Design of cost effective hydrogen storage devices should be a priority for practical use of hydrogen fuel cells, particularly in automobiles. The construction of appropriate delivery systems will require a commitment of at least 20 years to build the necessary infrastructure.

Third, two different detailed designs and cost analyses were performed for hydrogen production. One design looked at a plant that produces hydrogen from natural gas using existing steam reforming technology based on known kinetics. The price estimate was toward the low end of published values. A second more futuristic and speculative design was performed for hydrogen production using the sulfur/iodine thermochemical cycle powered by a nearby nuclear power plant. The production cost for this energy intensive system was found to be more than an order of magnitude higher than for the natural gas based plant.

From a team management point of view various challenges had to be tackled. At the beginning of the semester six teams were created each having their assigned tasks. During the semester it became obvious that communication with a team of 17 members became a major issue. We therefore decided to merge two teams and create an independent team that was responsible for collecting and managing data. Further as little was known of each individual's strengths and the labor required to accomplish certain tasks, a few selected members had to be reallocated to other teams during the project duration.

To provide an interface with the industry and other students / faculty members a website was created to display the accomplishments this team and the previous team have made. The site can be found under: <http://www.iit.edu/~ipro304cs4/> .

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1. Introduction

1.1. *Research Problem*

President Bush's National Energy Policy says, "In the long run, alternative energy technologies such as hydrogen show great promise." In response, Energy Secretary Spencer Abraham recently stated, "The President's Plan directs us to explore the possibility of a hydrogen economy."

There has been a lot of interest in this topic in the context of current world political, social, and economic events. Both the American public and private industry have been significantly affected by changes during the past couple of years and have had to react to these changes.

The continuation of a project to design and build a hybrid electric vehicle powered by a hydrogen fuel cell is the problem being addressed by this project team. Fuel cells utilize the chemical energy of hydrogen to produce electricity and thermal energy. A fuel cell is a quiet, clean source of energy. Water is the only by-product it emits if it uses hydrogen directly. Fuel cells have operating advantages for both stationary and mobile applications in that they are quiet and typically have high efficiencies at partial loads. They also have environmental advantages. For example, when pure hydrogen is used as the fuel, there are no emissions of sulphur or nitrogen oxides.

Hydrogen is a long-term solution to America's energy needs, with near-term possibilities. Hydrogen has the potential to solve two major energy challenges that confront America today: reducing dependence on petroleum imports and reducing pollution and greenhouse gas emissions.

A world-wide effort to achieve the hydrogen vision is underway but can only succeed through strong public/private partnerships, to address the issues involved in the introduction of a new vehicle infrastructure and distributed generation systems. There is general agreement that hydrogen could play an increasingly important role in America's energy future. Hydrogen is an energy carrier that provides a future solution for America. The complete transition to a hydrogen economy could take several decades.

1.2. *Project Vision*

The ultimate goal of this project is to perform a 100-mile drive with a small single-person hybrid electric vehicle using a hydrogen fuel cell to charge a series of custom-built Li-ion batteries. These batteries are designed with a passive cooling system, which employs a phase change material to keep the operating temperature

of the batteries as low as possible. There are safety aspects of the Li-ion battery systems that require keeping the batteries at a low temperature.

The vehicle is designed to run with eight Li-ion cells. While four cells are employed to provide the vehicle with the required power, the other four cells are being charged by the fuel cell. When the power of one battery bank goes dead the driver can manually switch to the other set of batteries, which have been fully charged.

In addition to the construction and performance of the hybrid electric vehicle, the team has also completed the design of a two theoretical hydrogen production plant models. One plant uses natural gas to create hydrogen, the other uses a sulfur/iodine thermochemical cycle powered by nuclear energy.

2. Background / Purpose of Project

The ultimate goal of this project is to perform a 100-mile drive with a small single-person hybrid electric vehicle using a hydrogen fuel cell to charge a series of custom-built Li-ion batteries. This project is a continuation of last semester's IPRO that dealt with the same problem. The last IPRO was not successful in completing an extended drive for the test vehicle and were only concerned with charging the batteries separately from the functionality of the vehicle.

These batteries are designed with a passive cooling system, which employs a phase change material to keep the operating temperature of the batteries as low as possible. There are safety aspects of the Li-ion battery systems that require keeping the batteries at a low temperature.

An additional problem tackled in this semester's IPRO was to develop a true hybrid system that allowed for a set of batteries to run the vehicle while another set of batteries were being charged via power supplied by the fuel cell. The vehicle is designed to run with eight Li-ion cells. While four cells are employed to provide the vehicle with the required power, the other four cells are being charged by the fuel cell. When the power of one battery bank goes dead the driver can manually switch to the other set of batteries, which have been fully charged. If all aspects of the course were successful, the vehicle should be able to run continuously, until the on-board hydrogen supply ran out.

In addition to the construction and performance of the hybrid electric vehicle, the team has also completed the design of a two theoretical hydrogen production plant models. One plant uses natural gas to create hydrogen, the other uses a sulfur/iodine thermochemical cycle powered by nuclear energy.

3. Research Methodology and Assignments

Due to the nature of the project and the large number of students involved, the project was divided into (7) teams. There were only three teams in the last IPRO. The additional teams allowed for much more work to be accomplished in this IPRO. The dedicated website team incorporated the information from the last IPRO as well as the completed set of documents generated from this IPRO. A great deal was learned about actually constructing and hybrid circuitry and the testing has begun. The large number of chemical engineering students allowed additional work to be completed in engineering two separate hydrogen production facilities as well as completing a survey of the economics of hydrogen production, storage and transportation options. The background and purpose of each team is discussed below:

Battery Team

They had the responsibility to build and back-up battery and to test the existing batteries and generate data in the performance. The battery cells were housed in aluminum foam, which evenly distributed the heat generated by the batteries. A phase change material (PCM) was also used to absorb the heat generated by the batteries without raising the overall bank temperature. Safety circuits were also connected to the batteries to prevent over and undercharging of the batteries. The group also constructed a case for the batteries capable of withstanding the operating temperatures. The initial objectives of the battery team were to ensure that the batteries were working properly for the trial runs.

Fuel Cell Team

The Fuel Cell Team did not have the necessary electrical engineering knowledge in order to complete the objectives. It was also discovered that, in order for the Hybridization Team to complete their objectives, they needed to obtain data required themselves. At this point, it was decided that there was no need for the Fuel Cell Team: the team was dismantled and the members were reassigned.

Hybridization Team

Throughout the course of the semester, the objectives of the hybridization/fuel cell teams have been altered to reflect changes in the design goals. Originally, there were two separate groups, the Hybridization Team and the Fuel Cell Team. The goal of the Hybrid Team was to design a feasible hybrid system that could be implemented between the fuel cell and the batteries, allowing the cart to run primarily on power from the fuel cell. It was soon realized that the complexities

involved in such a charger meant that an efficient design was beyond the scope of our limited time and expertise. One of the team sponsors, Microsun, built a custom designed charger. Our responsibilities now include incorporating the charger with the fuel cell. In the proposed system, the fuel cell will charge one bank of batteries using the charger, while another bank powers the electric motor. When the latter bank runs out of charge, the battery banks are switched. So now the pack that was being charged provides power, while the drained bank is charged by the fuel cell.

Vehicle Design Team

The objective of the Vehicle Design Team involves the mechanical aspects of the wheel chair and fuel cell combination. The team designed and built a trailer assembly to house the fuel cell, hydrogen tanks, and batteries. The future objectives are to develop the required documentation package and instructional manuals to facilitate user training and maintenance.

Business Team

Initially the business team consisted of 4 members. After the reorganization of the project the business team was expanded to take account of the requirements required for the chemical engineers (CHEE). The team was split into three main sub-groups: (1) Investigate the safety aspects of hydrogen use, (2) Examine the design of two hydrogen production facilities (natural gas supplied and non-fossil fuel based), (3) survey on the economics of hydrogen production, storage and distribution.

Knowledge Team

The goal of this team is to solicit, gather, and organize existing data and procedures for this IPRO and future IPROs, in order to enhance the productivity of the teams and their members and to provide a frame of reference for new members, any future members, or any group who may assist this IPRO.

Website Team

The objectives of the website team were to redesign the main layout of the website; create a site which incorporates information from the old site and current information from this semester's group, create detailed documentation of the website, and make important documents available online as they become available.

4. Process Description

4.1. *Motor (The System Load)*

The vehicle runs on an electric motor that runs on 24 volts of electricity. The 24 volts is not the maximum limit, but rather closer to the minimum requirement of the motor. This means the motor can run at higher voltages: up to 35V+.

Now the original vehicle ran on two 12 volt lead acid batteries in series, which gave a combined 24 volts. Our objective is to run the same electric motor with power supplied from the fuel cell and from lithium ion batteries. To accomplish this, the lead acid batteries were simply disconnected and the motor's power leads were connected to the power output of the combined fuel cell/battery power control circuit.

Power Consumption

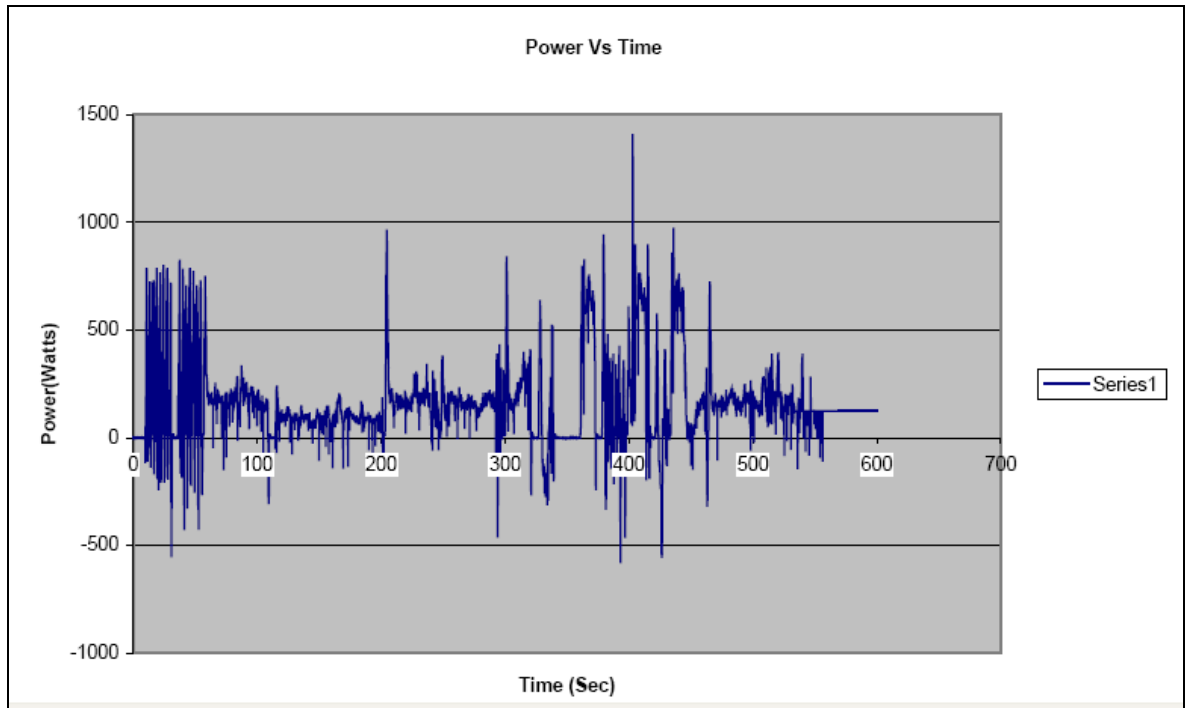
The motor on the scooter has a nominal power of 530 Watts, with a corresponding nominal current of 22 amps. However, experiments to determine its power consumption showed that on average the motor consumes about 300 watts. 300 watts is used when the vehicle is running at a constant medium speed range over flat ground. Now, the electric motor needs a high current to start from the 'off' state. This current is high – up to 50 amps at 24 volts. However, this peak power demand lasts for a short time, the order of a few seconds or less, until the motor has enough rotational velocity. As the rotational velocity increases, all electric motors develop a back emf., i.e. a reverse voltage which impedes the current flowing into the motor, thereby lowering the initially high power demand.

Traveling High Speed or up an Incline

While traveling at higher speeds, or when climbing against an upward gradient, the motor, as expected draws more power, near 500 watts or more. This proved to be a major factor in shaping our design work. This was because the system we built had to provide enough power for such situations, since lowering the performance of the vehicle was not an option.

The following graph shows the power demand of the electric motor over a period of time:

Figure 1: Power Demand of Electric Motor over a period of 10 minutes



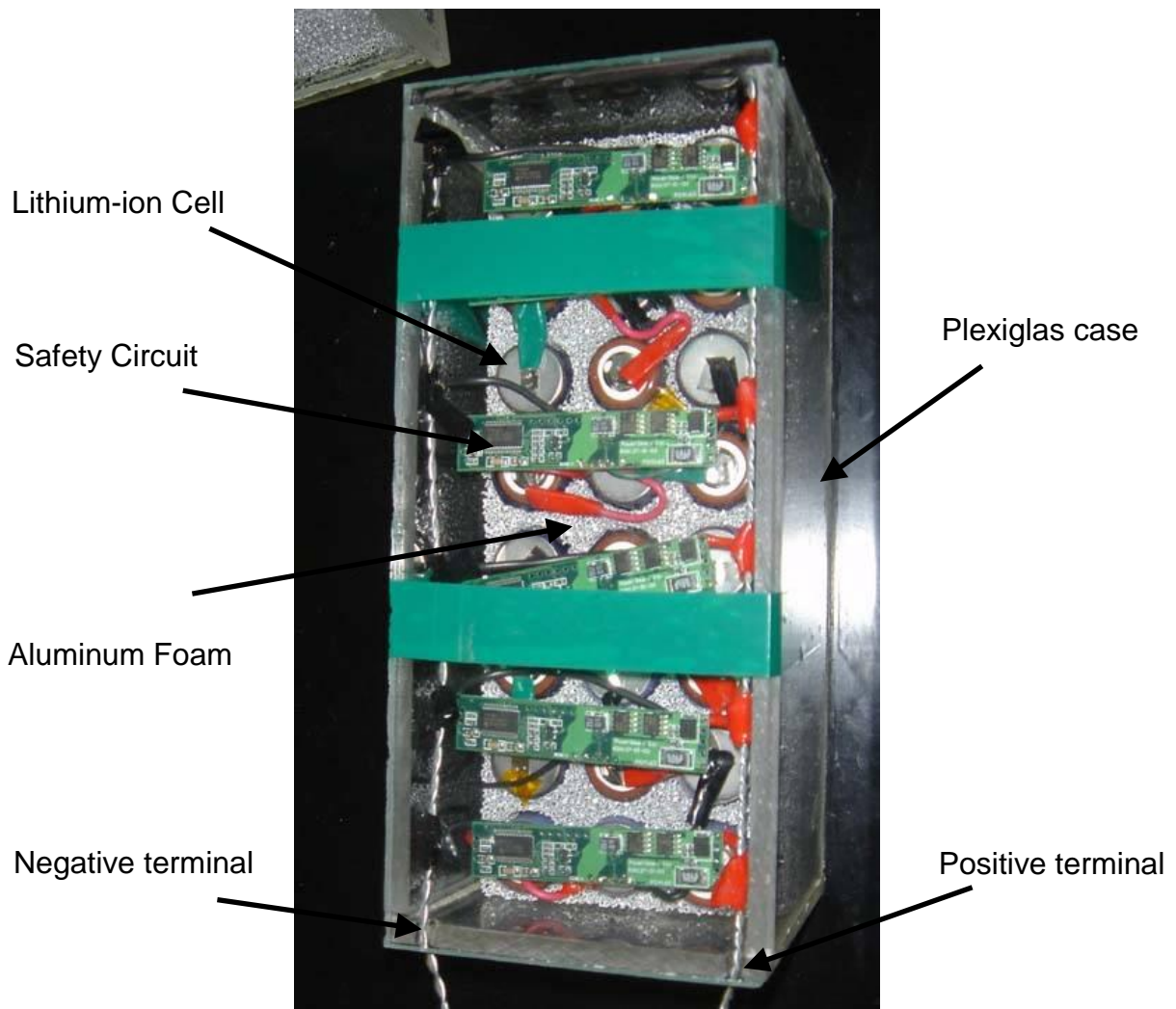
Source: *Final Report for IPRO304c, Spring 04*

4.2. Batteries

4.2.1. Description of Batteries

Lithium-ion batteries made during the spring 2004 IPRO are currently being used to provide power for the wheelchair. The batteries currently consist of 24 individual lithium-ion cells, a brick of aluminum foam, 240 g of paraffin wax (not shown in figure 2), 6 safety circuits, and a Plexiglas case. These components are shown in figure 2.

Figure 2: Single Lithium-Ion Battery Pack



The operating characteristics and specifications of the lithium-ion cells and battery brick are given in table 1.

Table 1: Operating characteristics for individual cell and battery brick

	Energy Capacity (A-hr)	Operating Voltage (Volts)	Mass (kg)
Individual Cell	2.4	3.67	.045
Battery Brick	14.4	14.68	1.4

The lithium-ion cells are currently arranged in the following manner: four cells connected in series, and six packs of four connected in parallel. This is given by the designation 4S X 6P. The safety circuits are installed to prevent over and undercharging of the batteries. If the current or voltage in the battery reaches an undesirable level, the safety circuits cut the power so no damage is incurred by the battery. For a detailed procedure on charging the batteries, interested readers are referred to the end of this document. The Plexiglas case is put in place simply to hold the contents of the battery.

4.2.2. Operation and Setup

When the lithium-ion cells are being used, they produce heat that must be dissipated by the battery. The aluminum foam is used to evenly distribute the heat throughout the battery and prevent the formation of heat pockets within the battery. Although the aluminum foam evenly distributes the heat, this heat can cause the temperature inside the battery to reach a dangerous level that can damage the lithium-ion cells. Therefore, the paraffin wax is used to absorb this heat. This phase change material (PCM) absorbs the heat, but does not cause the temperature of the battery to increase keeping the batteries at a safe operating temperature.

It was decided at the beginning of the semester that it would be beneficial to have a case to hold four batteries at a time. This way it would be easier to change batteries during a test drive of the wheelchair. So it was decided that two acrylic cases would be made to hold four batteries in a “battery bank.” The acrylic cases were made with a hinged top to provide easy access to the batteries. In addition, holes were drilled in the acrylic cases to provide air flow around the battery bricks for additional cooling. The next step in the thermal management of the batteries is the determination of the optimum amount of wax required to keep the batteries at a safe

operating temperature. A heat transfer analysis performed by Rita Buresh is summarized below.

4.2.3. Heat Transfer in Phase Change Material of Li-Ion Batteries

As stated previous, the Li-ion cells used in the battery modules were 1.5 Ah Panasonic 18650 Li-ion cells modified to provide 2.0 Ah. Each battery module contains 24 cells packed in Doucel Aluminum foam and the phase change material (PCM), paraffin wax. The aluminum foam has a density of 8-10% with ~ 44 pores per inch. Table 2 shows the design specification of the Li-ion cell.

Table 2: Specifications of the 18650 Li-ion cell

Nominal voltage	3.67 V
Nominal capacity	2.0 Ah
Energy	7.34 Wh
Size	Diam: 18 mm, length: 65 mm
Weight	42 g
Energy Density	
Gravimetric	160 W*h/kg
Volumetric	300 W*h/l
Charge duration	2-4 h (100%)
Operating specifications	
Operating voltage	4.2-3.0 V
Charge voltage	4.2 V \pm 50mV
Cut-off voltage	3.0 V
Temperature range	-20 to 60°C

Source: Design and simulation of a lithium-ion battery with a phase change material thermal management system for an electric scooter. J. Power Resources 128(2004) 292-307

The Li-ion cell module was simulated as an unsteady state, two-directional heat transfer model. The properties of the Li-ion cell were determined through experimentation with an accelerating-rate calorimeter during charging and discharging cycles. Studies of the temperature profile in a model Li-ion battery module found temperature gradients of 10°C between the center of the battery and the cell discharging location. A larger gradient of 20°C was found between the air at the center of the module and the air at the module surface that is exposed to forced air-draft convection. The large deviations in temperature through the module greatly affect the performance of the Li-ion cells, which have optimum output at 25°C. Li-ion cells have significant capacity degradation and shortened calendar life when exposed to temperatures greater than 60°C. A more serious concern for Li-ion

batteries is thermal runaway that can result in fires and more significant damage, which starts in the temperature range of 70-100°C.

The safety circuit is one necessary element to prevent overcharging of the Li-ion cells. Other options to prevent battery overheating include passive cooling systems such as forced air-cooling systems, liquid-cooling systems, and PCM thermal management systems. Implementing a PCM thermal management system is advantageous over other cooling systems since it eliminates the extra energy requirements to circulate a cooling medium and does not require as much space on the vehicle. For the batteries on the transporter, paraffin wax was chosen as the phase change material for its ideal properties of a low melting temperature and relatively high latent heat. The paraffin wax is distributed through the aluminum foam mesh. The foam serves to enhance the thermal conductivity of the PCM and to distribute the heat to regions further from the cell surface. The thermal conductivity of paraffin wax in solid phase is 0.21 W/m K, while the thermal conductivity of the aluminum foam is approximately 3.0 W/m K. This dramatically helps the dispersion of heat.

The mass of the PCM required is determined by equation 1:

Heat discharge of cell = Sensible heat + Latent heat

$$Q_{disch} = m_{PCM} C_p^* (T_m - T_i) + m_{PCM} \lambda \quad (\text{Eqn 1})$$

Where:

- Q_{disch} = Heat generated by the Cell at discharge
- C_p = Heat Capacity
- T_m = Melting Temperature of the PCM
- T_i = Initial Temperature of the Module
- λ = Latent Heat of Melting

The properties of Paraffin wax can be seen in table 3. The heat absorbed by the aluminum foam is considered negligible and is not considered in the PCM mass calculations.

Table 3: Properties of Paraffin Wax

Melting Temperature	40-44°C
Latent Heat	195 KJ/kg
Specific Heat	1.77 KJ/kg K
Thermal Conductivity	
Solid Phase	0.21 W/m K
Liquid Phase	0.29 W/m K
Density	
Solid Phase	822 kg/m ³
Liquid Phase	910 kg/m ³

Source: Design and simulation of a lithium-ion battery with a phase change material thermal management system for an electric scooter. J. Power Resources 128(2004) 292-307

Using the values in tables 2 and 3, it can be determined that 9 g of PCM is required for each 18650 Li-ion cell. For the Li-ion battery module that contains 24 cells, a total mass of 216 g of paraffin wax should be used to prevent overheating of the battery.

Volume expansion occurs during the cooling and solidification of the paraffin wax, which can induce stress on the battery casing and potentially crack the casing. As a result, an extra 10% of volume was allowed in the battery casing. Also, the battery casing had to be made entirely leak proof on all edges to prevent any loss of the PCM during operation. More recently, it has been found that the paraffin wax causes corrosion on the battery terminals, which affects the performance of the module. Suggestions for improving the heat transfer through the battery include adding aluminum fins to the surface of the battery to increase the heat transfer area or using different phase change materials.

4.2.4. Future Recommendations

One problem with the current design of the batteries is the gauge wire used to connect the safety circuits to the battery. The wires at this time are too large, and copper strands must be cut in order to make the wire fit in the connections on the safety circuits. When copper strands are cut, this leaves wire exposed. If this exposed wire comes in contact with any other wires connected to the safety circuit, it can cause the safety circuit to short. This happened more than enough times during the project. Therefore, it is the battery team's recommendation that a larger gauge wire be used to prevent this problem in future projects.

As stated earlier, an aluminum foam block is currently being used to evenly distribute the heat throughout the battery brick. The major disadvantage to this design is cost. The aluminum foam is very expensive, and research is presently being conducted to develop a cheaper alternative. This alternative is carbon powder compressed into a block. This carbon material is a lot cheaper and can be designed to provide the same thermal response as the aluminum foam. A specific mass of carbon powder is compressed into a block. Then paraffin wax is melted in a container and the carbon block is placed in it. The carbon block then absorbs the wax until saturation. Thermal testing is being conducted to determine whether the thermal conductivity is sufficient to provide the thermal relief necessary for safe operation of the batteries.

4.3. Fuel Cell

4.3.1. Background

In recent years, a lot of progress has been done regarding the research and development of fuel cells. Now fuel cells are a very clean and highly efficient source of electric power. The only exhaust from a fuel cell is water vapor. Different types of fuel cells take in different types of 'fuel', but all these chemical fuels have one thing in common: they have a high amount of hydrogen either as a compound, or simply, when hydrogen is directly used as the fuel, in elemental gaseous form. The fuel cell takes oxygen from the air and combines it with hydrogen from the fuel. This combination does not take place directly, that is, the chemical process is not a simple combustion. The combination takes place through a membrane in an electrolytic process which produces electricity and water vapor.

Electricity thus is produced directly without the need of any generator. However, conversion circuitry is needed within the fuel cell to convert this power to a steady electric supply that can be used reliably for different applications. The electricity production process is very efficient depending on the membrane used, typically 30-40%, while some fuel cells that re-use waste heat energy of the chemical process, have up to 80% efficiency.

For its advantages as an environmentally friendly power source, our team's objective is to incorporate the fuel cell to power the electric people transporter.

4.3.2. Specifications of the Fuel Cell

For the purposes of our research, one of our sponsors, Avista Labs donated us a fuel cell: the *Independence 500*. This fuel cell runs on pure hydrogen gas and air. The fuel is designed for stationery battery charging applications. The output of the fuel cell is 52 volts constant and a maximum current output of 10 amps (thus about 500 watts power output). It also has a second voltage output: a varying voltage between 51-55 volts.

However, the fuel cell has a drawback, which is it needs an external power source to start operating. It needs an external voltage of source of 35-40 volts initially to start operation. But once it has turned on, this external source can be removed.

Specifications of the fuel cell as provided by the manufacturer now follow.

500W PEM fuel cell

independence 500™

Introduced in 2002, the Independence 500™ is a 500-watt fuel cell system specifically designed for battery-charging applications. The product will affordably add hours of backup run time as well as extend battery life. It can be mounted in a standard 19-inch rack. The Independence 500™ is powered by ten of Avista Labs' hot-swappable 250 series modular power cartridges.



The Independence 500™ is quiet and generates electricity using industrial-grade hydrogen, with the only by-products being pure water and a little heat. Using Avista Labs' patented Modular Cartridge Technology™, the 250 series cartridges can be replaced

as needed while the unit continues to power a load.

The Independence 500™ is CSA International certified to safety and performance standards.



Specifications

Power Output:	
Continuous	500w
Voltage:	Optional 12, 24, or 48VDC
System Start-up Time:	
50% power	< 1 minute @ 25°C
100% power	< 2 minutes @ 25°C
Operating Conditions:	0°C – 45°C (32°F – 113°F)
Efficiency:	36-40% @ full load
Fuel Supply:	Industrial grade H ₂
Supply Pressure:	3-6 PSI
Fuel Consumption:	9 SLPM @ 500w 5.5 SLPM @ 250w
Size:	42.7cm h x 44.7cm w x 47cm d (16.8" h x 17.6" w x 18.5" d)
Weight:	78 lbs.
Operating Mode:	Battery charger
Start-up Modes:	Remote, auto or manual
Noise:	-53 dBA @ 1 meter



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6,218,005; 6,307,550; and other patents pending. Product
specifications are subject to change at any time.

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Drawbacks of the fuel cell

The fuel cell has a number of drawbacks which are stated as follows:

- a) As stated before, the fuel cell outputs a maximum of 500 watts only. Our electric motor may need more power than that. The problem is that if current demand from the fuel cell exceeds 10 Amps (i.e. power demand more than 500 watts), the fuel cell immediately shuts down.
- b) There is a significantly high lag time between change in power demand from the fuel cell, and the fuel cell's response time. This delay is in the order of couple of seconds. That is, suppose the fuel cell is giving out 100 watts; and then we want to draw 400 watts from the fuel cell. The fuel cell will take a couple of seconds to provide this increased power: the output of the fuel cell, over several seconds, increases slowly from 100W to 400W.
- c) The fuel cell cannot be operated in temperatures below the freezing point of water. However, in our geographical location, such temperatures are common for several months of the year.
- d) The fuel cell's size takes away the possibility of fitting it onto the scooter itself.

These drawbacks composed the major design challenges that our team had to face. The problem of its size was easily dealt with by attaching a trailer to the back of the vehicle and mounting the fuel cell on the trailer. We will discuss about our solution to the drawbacks mentioned in (a) and (b). As for operating in cold temperatures, we have so far been unable to find a solution to the problem, other than not to run the vehicle outdoors if the weather gets too cold.

4.3.3. Challenges faced by the Team

Fuel Cell Operation

In the early part of the semester, we were getting delayed because most members did not know how to operate the fuel cell. However, this was solved and we were trained by a research assistant about how to operate it. One of our major accomplishments was to document what we learned in extensive detail. The Appendix contains the fuel cell's operating manual as documented by the hybridization team, as well as other equipment.

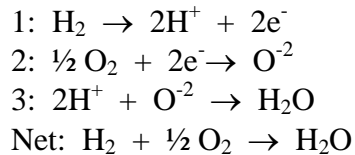
Problems with the Fuel Cell-Battery Interface

In the beginning of the semester, we were using a simplified system for charging the battery from the fuel cell. This system was so inefficient that it caused unbalanced charging of the batteries and only charged them very little. It was soon realized that this simple charger would not do. As a result, it was decided to build a new charger that would draw power from the fuel cell and channel it to the batteries.

The fuel cell team was originally given the responsibility of designing the charger. However, it was soon realized that the complexities of the factors involving the batteries would make the task of an efficient charger design very difficult given the time constraints and lack of the expertise required. This was a major obstacle that we faced during the semester. Fortunately, one of our sponsor companies, Microsun, agreed to build a professional-grade charger for us. Details of this charger follows in the hybridization section.

4.3.4. Hydrogen Fuel Consumption Calculations

The fuel cell produces energy based on the reduction reaction of hydrogen, which in turn reacts with oxygen from air to produce water vapor. The reaction set is as follows:



Since oxygen from the air is supplied in excess to the fuel cell, the reaction of concern is the reduction of hydrogen, reaction 1. Using this reaction the equivalent molar quantity and mass of hydrogen per hour-Amp can be determined by the following relation.

$$\begin{aligned} n_{\text{H}_2} &= \frac{1\text{C}/\text{sec}}{1\text{Amp}} * \frac{1\text{equiv. } e^-}{96487\text{C}} * \frac{1\text{mol H}_2}{2\text{equiv } e^-} * \frac{3600\text{sec}}{\text{hr}} = 0.01866 \frac{\text{mol}}{\text{hr} * \text{Amp}} \\ m_{\text{H}_2} &= \frac{0.01866\text{mol}}{\text{hr} * \text{Amp}} * \frac{2.02\text{g H}_2}{1\text{mol H}_2} * \frac{1\text{kg}}{1000\text{g}} = 3.77 * 10^{-5} \frac{\text{kg H}_2}{\text{hr} * \text{Amp}} \end{aligned}$$

The amount of hydrogen can be determined for a given power and voltage specification. For example, the fuel cell provides 500 watts of power with a total voltage of 48 V. Since the fuel cell operates at 35% efficiency at full load, the current, i , and the amount of hydrogen required can be determined.

$$i = \frac{P}{V} = \frac{500}{48} = 10.417 \text{ Amp}$$

$$M_{H_2} = 10.417 \text{ Amp} * \frac{3.76 * 10^{-5} \text{ kg } H_2}{\text{hr} * \text{Amp}} = 3.92 * 10^{-4} \frac{\text{kg } H_2}{\text{hr}}$$

$$\varepsilon = \frac{U_{Consumed}}{U_{Feed}} \rightarrow 0.35 = \frac{3.92 * 10^{-4} \frac{\text{kg } H_2}{\text{hr}}}{U_{Feed}} \rightarrow U_{Feed} = 0.0011 \frac{\text{kg } H_2}{\text{hr}}$$

The efficiency value was determined by specifications from the fuel cell manufacturer and no information was found in regards to the fuel cell efficiency at different operating conditions. Using the stated conditions and stoichiometry, equivalent amounts of air in the feed can be determined. It is assumed that air consists of 20.9% oxygen and 79.1% nitrogen.

$$M_{O_2} = \frac{0.0011 \text{ kg } O_2}{\text{hr}} * \frac{1000 \text{ g}}{1 \text{ kg}} * \frac{1 \text{ mol } H_2}{2.02 \text{ g } H_2} * \frac{1 \text{ mol } O_2}{2 \text{ mol } H_2} * \frac{38.0 \text{ g } O_2}{1 \text{ mol } O_2} = 0.0103 \frac{\text{kg } O_2}{\text{hr}}$$

$$M_{air} = \frac{0.0103 \frac{\text{kg } O_2}{\text{hr}}}{0.209} = 0.0495 \frac{\text{kg air}}{\text{hr}}$$

Based on the storage conditions, the volume of hydrogen and air can also be determined by the gas law and appropriate correlations. All values are based on specifications of the fuel cell. The fuel cell performance and efficiency at different operating conditions were not tested by experimentation due to time restrictions.

4.3.5. Future Improvements

This project can certainly benefit with improvements surrounding the fuel cell. The following improvements could help us:

- a) The fuel cell is our main source of power, and therefore a more powerful and efficient fuel cell will certainly help us. For an efficient hybrid vehicle, we need a fuel cell with a power output of at least 750 watts, 1 kilowatt being better.
- b) The fuel cell's size makes a trailer essential for the project. However, the trailer takes up a lot of space, and adds a lot of mass to the entire vehicle. This means, the vehicle requires more power to run, which is undesirable. Thus a light and compact fuel cell is desirable.
- c) The fuel cell we have has a response time which is slower compared to newer models. The hybrid vehicle needs to have a high response time and therefore it will be good to have a fuel cell with a higher response time.

4.4. Hybridization

4.4.1. What is a Hybrid System?

The word hybrid stems from the Latin word “hybrida” which means “to bring two things together.” Originally meant to define words from two different origins, it now is most commonly referred to regarding a huge and developing automotive industry. A hybrid drive system is one that incorporates two different forms of power and effectively uses them as one.

The best way to understand the advantages of a hybrid vehicle is to think about a car traveling down a highway at the posted speed on level ground. In this case, the engine is doing three things:

1. It is overcoming rolling resistance in the drive train.
2. It is overcoming air resistance.
3. It is powering accessories like the alternator, the power steering pump and the air conditioner.

The engine might need to produce no more than 10 or 20 horsepower (HP) to carry this load. Cars have 100- or 200-horsepower engines to handle acceleration from a standing stop, as well as for passing and hill climbing. The maximum HP rating is used for only 1% of driving time. The rest of the time, the weight and the friction of the engine must be carried, which wastes a lot of energy.

Our IPRO decided to take this concept one step further. By using the clean technology of hydrogen fuel cells, along with the reliable power of new lithium ion battery technology, a new kind of hybrid is produced. This uses a fuel cell-battery combination to power a vehicle, in this case, the electric people transporter. The following section will help to outline our hybrid system, as well as its advantages.

4.4.2. Major Accomplishments

Design of a working hybrid system was one of the major challenges faced during the team. This was tackled by the ‘Hybridization Team’. Due to the time constraints, we could not build a fully working hybrid control system for the vehicle. However, we designed a hybrid control system, and have also designed and built a separate semi-hybrid system for running the vehicle.

- a) The semi-hybrid vehicle uses the fuel cell to charge the one pack of batteries. When this pack is being charged, another pack of lithium ion batteries powers the scooter. The packs are switched by a semi-automatic control box. So although the motor is run directly by the batteries, the system is semi-hybrid

since the fuel cell, charging and discharging systems are incorporated in one complete circuit.

- b) The hybrid circuit system that we have designed takes a more direct approach for powering the electric motor. In this design, the fuel cell powers the electric motor most of the time. The lithium batteries are there to provide bursts of power as and when the vehicle requires. The batteries can provide more than 500 watts and can thus meet the maximum power requirement of the motor, but since they run out of stored energy after a while, they will be used only part of the time. The circuit incorporates several buffers between the fuel cell and the electric motor in order to improve the response time and also protect the fuel cell from damage.

4.4.3. Major Design Challenges

The major design challenges faced by the hybrid team are as follows:

- a) A working charging system for the lithium ion batteries: Since the lithium ion batteries have two charging modes with varying current and voltage requirements, this was a difficult task for the team. The hybrid team out-sourced this responsibility to *Microsun*. This guarantees that the chargers to be used for the project are high quality and meet all the requirements posed by the batteries.
- b) The power output of the fuel cell was significantly lower than the maximum power requirement of the vehicle. To make matters more complicated, the fuel cell shuts down immediately if the power demand is exceeded by 500 watts.
- c) The fuel cell's response time is low.
- d) The different parts: the motor, batteries, and the fuel cell operate at, or require different voltages to operate than each other.

The second factor was tackled by the semi-hybrid system as follows: the fuel cell does not directly power the electric motor, but rather, the batteries do. In this manner, the third challenge is also addressed.

The hybrid circuit designed uses the same chargers built by Microsun. It tackles the second factor by using big capacitors and batteries to handle peaks in the motor's power demand. The issue with the fuel cell's response time is tackled by using a system to keep the power demand from the fuel cell nearly constant and close to the maximum power requirement of 500 watts.

For the fourth design challenge, both the systems use dc/dc converters for voltage matching. Two batteries used in series help the motor to get the desired operating voltage from the batteries.

How the design challenges were addressed are described in more detail in the sections that follow.

4.4.4. Charging Circuit

4.4.4.1. Purpose

While the transporter could be driven at the end of last semester, there was not an acceptable charging system in place. The overall goal of this semester was originally to develop and implement a hybrid system to power the transporter. Part way through the semester it became apparent that achieving that goal in full was unlikely. The decision was then made to use a switched system, one where the fuel cell did not power the motor directly. The thought was that such a system would simplify what needed to be accomplished by the end of the semester, and the parts from that system could be reused in the hybrid design at some later point.

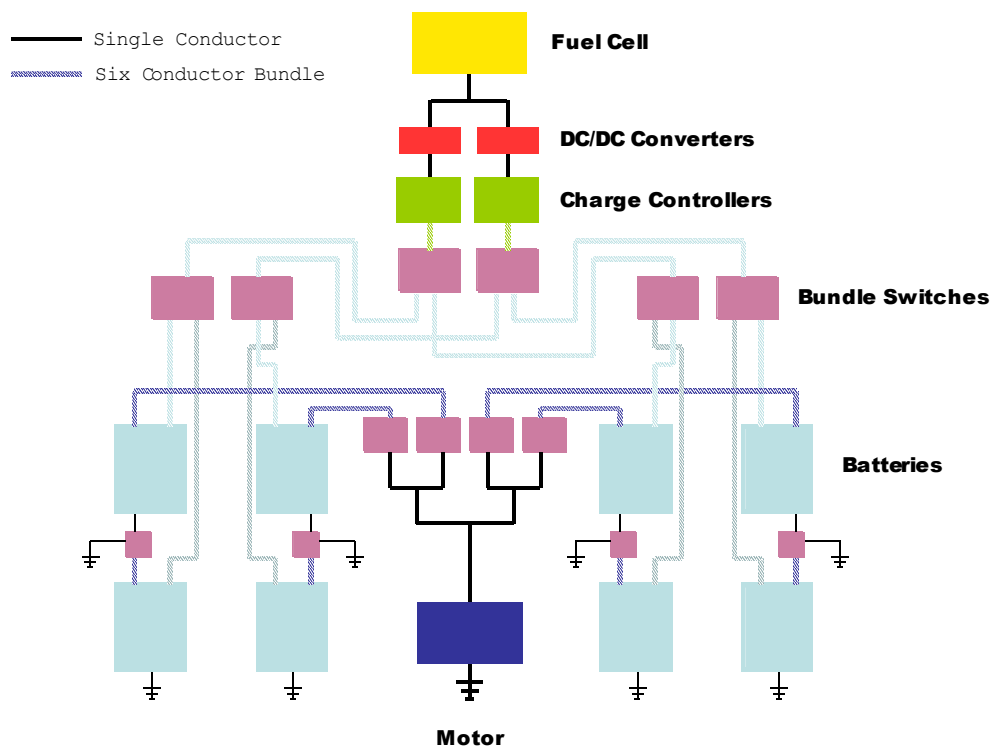
4.4.4.2. Requirements of the Charger Circuit

Charging lithium ion batteries is not as simple as just applying an over voltage to the cell. For proper conditioning, a charge controller is needed to charge the cells at constant current. Professor Al-Hallaj contacted Microsun Inc, one of our sponsors for this project to find out if they could deliver such a charge controller. The battery configuration consisted of four battery packs, each with 4S6P cells (four parallel six series). Microsun agreed to supply 2 charge controllers, each of which could charge 6 strings of 4 batteries in parallel. To properly charge the cells, they required that each string have separate contacts. Thus the first goal of the charger team was to rewire two battery packs to provide leads to each string of cells. The two charger units supplied by Microsun required 24V and 10A each. The second goal of our team was then to find a way to step down the voltage of the fuel cell. It was decided to purchase two DC/DC converters from Pico Electronics. Each would take in 55V and just under 5A, and output the required 24V and 10A.

4.4.4.3. Switching Design

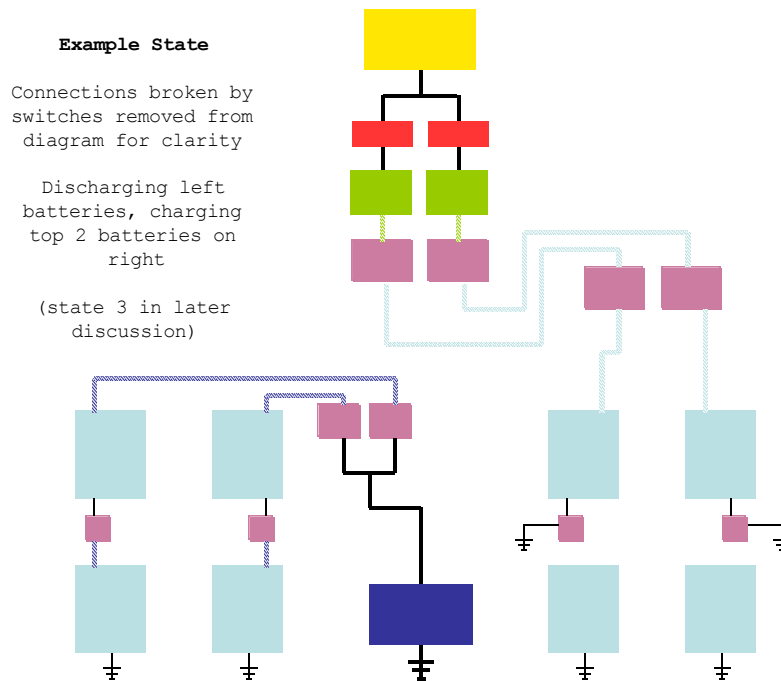
Once the charge controllers and necessary power conditioning for them were obtained, a method for charging different battery packs without rewiring anything was needed. Seeing as the charger could only charge 2 packs at a time, while 2 packs were dormant and the other 4 provided power to the motor, the switching system was not simple. Each charge controller had a common and 6 positive leads, 14 leads in all, that needed to be connected to any pair of batteries by throwing a switch. It was decided to use relays to achieve this goal. By wiring the control signals of several relays together, it is possible to switch bundles of wires together. This was ideal for the situation we had. Switching was needed to provide a way of directing power through a tree of bundles to the correct battery packs. The basic schematic of that system is below:

Figure 3: Basic Schematic of Charging Circuit



This overall diagram doesn't speak well to the function of the system, but is provided for completeness. A sample state is provided below to show the system in action:

Figure 4: Sample State for Charging Circuit



Here we see two of the batteries being charged, while the four on the right power the motor. Early on it became clear that all of these switches should be combined into a single box. S 4PDT relays with sockets were purchased from Digi-Key to accomplish our task, as well as an aluminum enclosure and required connectors. The finished product would be a single box with standard D-Sub9 connectors that could use off the shelf serial cables to connect each battery, each charger, and the motor to the switching box. We further planned to add gauges to the enclosure to monitor the charge level of the batteries. Each gauge would be accompanied by a pushbutton switch that would connect the charging system to that pair of batteries.

4.4.4.4. Accomplishments and Challenges

As of today, the above circuit has not been finished. The decision for this team to exist didn't happen until over half way through the semester, which was a significant source of delay. Also, delays in identifying required parts and taking delivery on them set us back further. Currently we have only taken delivery on one

of the two required DC/DC converters. Also, a mounting place for the converters with necessary trim circuits to adjust the output voltage needs to be designed and implemented. All of the components for the switching box have been delivered. Current hold ups include a lack of needed tools in the lab, which we hope to solve by using another faculty member's lab over the next few days. All of the components for the switching box have been procured. We will attempt to finish this critical component by the end of the semester. All in all, we were moderately successful. With limited time we designed a complicated system and procured all of the parts to build it. We are ready to construct the product, which should allow for continuous operation of the cart, and allow the 100-mile drive to occur, but we have now run out of time to complete our task. It should be straightforward for a future team to finish any building we are unable to complete using the detailed designs we developed.

4.4.5. Final Circuitry Design on a Theoretical Basis

This section extensively details the hybrid system that has been designed. I used the term 'Theoretical' since we did not have time to practically build and test this design. However, the hybrid team has high hopes about the design's practical feasibility. The design that has been conceived is detailed extensively in this section. The background section re-states some of the things already stated in the report. The restating is done because it should help the reader to understand the hybrid circuit better.

4.4.5.1. Background

Electric Motor

The motor on average requires 275-300 Watts of power, i.e. when it is running at constant speed. However, occasionally, it requires more power, up to a kilowatt, like when accelerating from a stop, or when climbing up an incline. When the electric motor starts, it requires a large amount of current to get the motor rotating. This current value is up to 60 amps when the motor is supplied with 32volts. Fortunately, this spike lasts only for a few milliseconds. The motor needs to be supplied with at least 24 volts.

Fuel Cell

The fuel cell outputs a maximum of 500 watts. The output voltage ranges from 51 to 55 volts. Clearly this value is much less than the maximum power-demand of the electric motor. There are 2 main drawbacks in the fuel cell:

- a) If current demand from the fuel cell exceeds 10 Amps (i.e. power demand more than 500watts), the fuel cell immediately shuts down.
- b) There is a significantly high lag time between change in power demand from the fuel cell, and the fuel cell's response time. This delay is in the order of couple of seconds. That is, suppose the fuel cell is giving out 100 watts; and then we want to draw 400 watts from the fuel cell. The fuel cell will take a couple of seconds to provide this increased power: the output of the fuel cell, over several seconds, increases slowly from 100W to 400W.

Batteries

The batteries can handle large amounts of power, enough for the electric motor. Each battery outputs between 12 and 16.8 volts. The output voltage indicates how much charge is remaining in the battery. A battery has safety circuits which shut down it down if the charge remaining drops too low. We need 2 batteries in series to power the electric motor. Each battery has 6 separate wires as the positive terminals (each from a safety circuit, and there are 6 safety circuits), and one wire in the negative terminal.

Chargers

As mentioned, Microsun has provided us with two chargers. Each charger has two charging modes: fast charging mode (250W power demand) and slow charging mode(125W). Each charger can charge one battery at a time. The charger has six output wires, each going to one of the six wires in the positive terminal of the battery. When the charger is off, it will not draw any power. So when using the two chargers, the following are the possible power demands we can get from them: 0W, 125W, 250W, 375W, 500W. To run a charger from the fuel cell, we need a DC/DC converter to step down from the fuel cell's voltage to 24volts. By the end of this semester, we should have both the chargers and both the DC/DC converters.

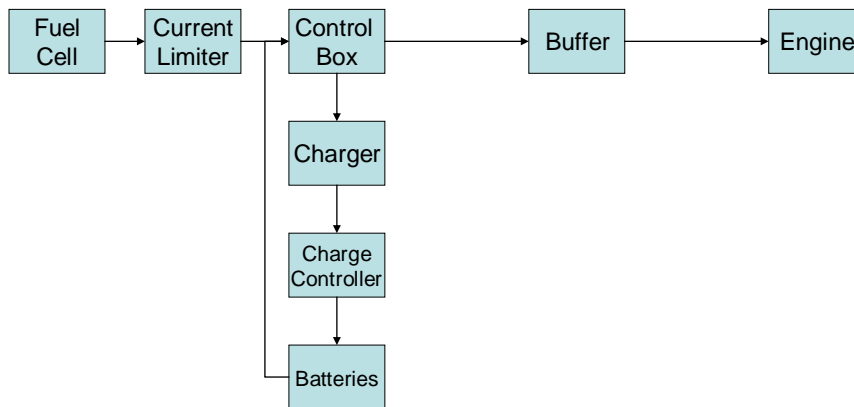
Bundle Wires, Bundle Relays

The semi-hybrid system that uses the two chargers uses several bundle relays in order to switch electric currents between its various components. The 6 positive wires from every battery form a wire bundle, and so do the 6 positive output wires from each charger. The bundle relays/bundle switches consist of several contacts that are adjusted at the same time.

4.4.5.2. Block Diagram for the Hybrid System

The hybrid circuit shown in this report is extremely detailed and can be difficult to follow without proper explanation. To simplify this, a block diagram has been created to show the basic components of the system.

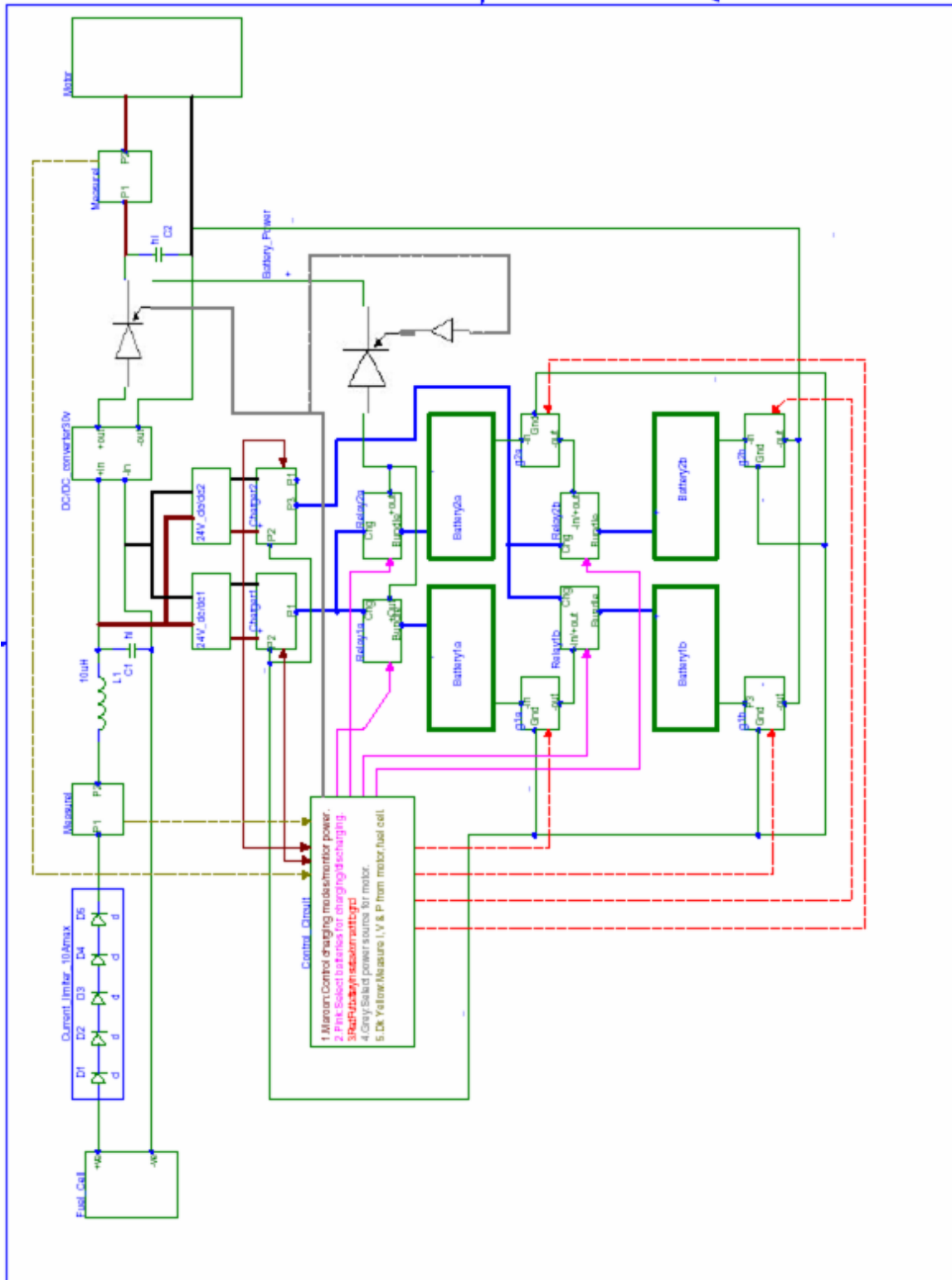
Figure 5: Basic block diagram of hybrid schematic



The solid lines in the block diagram represent the current flow and the arrows represent the direction. Although not shown in the diagram, each of the components is linked back to the control box, providing it real time information regarding operation of the scooter. This allows the entire circuit to adjust continuously throughout operation and provide optimal performance.

4.4.5.3. Hybrid Circuit Design

Figure 6: Schematic for theoretical Hybrid Control Circuit



4.4.5.4. *Basic Functioning of the Hybrid Circuit*

The hybrid circuit tries to make the best use of the parts that we have obtained during the semester to make use of the non-hybrid system. The circuit is designed so that it will provide a nearly constant 500 watts power demand for the fuel cell. It is hoped that the varying charging modes of the chargers will allow this to be achieved. In order to prevent the fuel cell from shutting down when the current demand exceeds 10amps, the circuit must have a current limiter. Normally the fuel cell supplies power to the electric motor. To step down the fuel cell's voltage to 32volts, a new dc/dc converter is required. To handle sudden current spikes, big capacitors are used which can handle the millisecond spikes that occur when the motor starts and which can also occur other times like when there is a sudden change in the power demand. The hybrid circuit switches to batteries for power supply only if the power demand exceeds 500watts and if the capacitors are unable to handle the increased power demand. There are two sensors which monitor the current output from the fuel cell, and the voltage and current going into the electric motor. These 2 sensors are used to coordinate the hybrid system.

4.4.5.5. *Part Details*

Current Limiter

The current limiter simply consists of several diodes in series, each having a saturation current of 10 amps. When a diode reaches the 10A limit, it adjusts itself so as to give an impedance (resistance) that varies and limits the current. The problem is that this impedance within the diode makes the diode use up power, and so the diode can get hot and even burn up.

$$\text{The Power absorbed} = \text{Current} * \text{Diode's Impedance}$$

So the idea is that, since the current limiter has several (up to 10) diodes, this power will be equally split up among each diode, and so there is much lesser chance of any diode burning up. Additionally, the entire hybrid system is such that the max 10A current will not last more than a few seconds, thus limiting the diode heating.

Thyristors

In the circuit diagram, the thyristors appear as diodes with arrows going into them. Thyristors are like relays. When an electric signal is applied (to the arrow), the thyristor switches off it was originally on, and vice versa. The 2 thyristors are configured inversely in the circuit. If one is off, the other is on and vice versa. That is,

if the fuel cell is powering the motor, the batteries are disconnected from the motor. On the other hand, if the batteries are powering it, then the fuel cell's output is disconnected from the motor.

Sensors

The first sensor detects if the 10A max current has been reached. When this happens, the control circuit makes necessary adjustments to limit this current, like for example, disconnecting the fuel cell's connection to the electric motor by means of the thyristor switch. The other sensor checks the voltage supplied to the motor, and this enables us to know if the capacitor is adequate to handle any current spike, or if we need to switch over to the batteries from the fuel cell.

Bundle Relays

The bundle relays are used to select batteries for charging and discharging. The bundle relays 1a,1b,2a,2d each take as inputs the bundle wire output of a battery's positive terminal, and 2 outputs. Depending on the relay's state, the relay connects the input to one output or to the second output. Simply, the relays are 2 way relays. The first output is used to connect the battery bundle to the charger bundle, or to connect the wires in the battery bundle to each other in order to connect them in parallel.

4.4.5.6. *Logic of Operation*

- 1) If the power demand of the motor is 200 watts, the fuel cell powers it. And the charging modes of the chargers are chosen so that they draw 250 watts.
- 2) When the power demand of the fuel cell jumps to 300 watts for less than a second and drops back to 200 watts, the capacitor handles the big spike.
- 3) However, if the motor's power demand stays at 300 watts, the fuel cell still powers it, but the chargers' charging mode is adjusted as follows: one charger is switched off and the second charger is set to draw 125 watts.
- 4) Then again, when the motor's power drops to 200 watts, the charging mode is again changed to draw 250 watts.
- 5) If the motor's power demand exceeds 450 watts and stays there for more than 2 seconds, thus making the capacitor ineffective, the fuel cell is disconnected from the motor by the thyristor. The g1, **or** the g2 relays then change their states so that they connect **a pair** of batteries in series, and supply the electric motor. The batteries then allow for the increased power demand of the motor. At the same time, the chargers are adjusted so that

they draw 500 watts from the fuel cell and charge the other pair of batteries which are not being used to power the motor.

The above examples show that the overall power-demand on the fuel cell is close to its full potential of 500 watts, including the dc/dc converters' inefficiencies and the current limiter's power draw. What this means is that the problem of the fuel cell's response time lag is eliminated. This is because power demand on the fuel cell remains nearly constant as demonstrated by the examples. Furthermore, the examples show how the switching between the various modes of operation limits the power demand on the fuel cell to 500 watts. This allows for an integrated hybrid system that prevents the fuel cell from shutting down and uses it most of the time to power the motor.

Finally, the chargers need batteries that can be charged. When both the two pairs of batteries become fully charged, no power will be drawn from the fuel cell at all. The chargers will be switched off, and only a pair of batteries in series will power the electric motor for several minutes until they become 40% drained. When the batteries reach 40%, the chargers can be operational and they are switched on. Thus the hybrid system is back in operation that allows for the fuel cell to power the motor directly. The second voltage sensor detects if this 40% is reached.

When a pair of batteries is being charged, the pair is charged until the pair reaches a high percentage of the batteries' possible storage capacity. During this time, the battery pair will never be used for discharging. Instead, the remaining pair of batteries is used for discharging and powering the motor if the need arises. However, if this discharging pair reaches 30% charge, the two pairs are interchanged. So now the battery pair having 30% charge will be connected to the chargers, while the other pair will be used for discharging. The bundle relays achieve this switching.

4.4.6. Simulating the System

Due to time constraints, the full system (the theoretical hybrid system) could not be simulated. However, significant progress has been made using Matlab and "Microsoft Visual Basic 6.0" software for simulation. A hybrid team member has worked on designing a computer model for the motor in Matlab, and another has made a Visual Basic program that is a basic simple model for the entire hybrid system that has been designed. The work is detailed below:

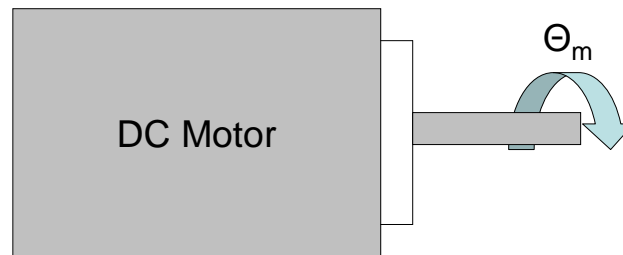
4.4.6.1. Motor Model

In order for the control system to be effective, there must be tolerances within the system. One of the most important of these is the speed at which the circuit reacts to fluctuating currents. Take the cruise control system of any automobile as an example. If the user wants to run the car at a constant speed of 55 mph, they then set the cruise control to respond accordingly. If the operation within the cruise control circuitry tried to keep the speed at exactly 55 mph, the ride would be incredibly uncomfortable and the wear on the engine would be devastating. This is avoided, however, with the use of a transfer function within the circuit. This gives the system time to respond to changing conditions and adjust accordingly, without overcompensating.

For the case of our electric motor, we'll have to make some reasonable assumptions regarding performance. The motor on the scooter has a nominal power of 530 Watts, with a corresponding nominal current of 22 amps.

The first step is to model the DC motor as a transfer function. Since all other parameters are based on the amount of power needed by the motor, it is the best place to begin analysis. Although some of the values are unknown, assumptions can be made that will allow for calculations to take place. As soon as actual values are known, they can be substituted to allow for more accurate calculation. A basic electric motor has the layout shown on the next page:

Figure 7: Basic DC motor diagram with rotational velocity



There are two different equations used to model the motor. The first uses the given torque on the system, and the second uses the emf voltage in terms of the rotational velocity.

$$T = K_t i_a \quad (\text{Eqn 2})$$

Where:

- K_t = Torque Constant
- i_a = Normal Current

as well as:

$$e = K_e \dot{\theta}_m \quad (\text{Eqn 3})$$

Where:

- K_e = Electric Constant
- $\dot{\theta}_m$ = Rotational Velocity

Applying Newton's law to both of these yields two practical equations:

$$J_m \ddot{\theta}_m + b \dot{\theta}_m = K_t i_a \quad (\text{Eqn 4})$$

$$L_a \frac{di_a}{dt} + R_a i_a = v_a - K_e \dot{\theta}_m \quad (\text{Eqn 5})$$

Constants for each of the equations have to be assumed. For a 500 Watt motor drawing roughly 25 amps in our scooter, it can be assumed that $J_m = 0.02 \text{ kg}\cdot\text{m}^2$, $b = 0.001 \text{ N}\cdot\text{m}\cdot\text{s}$, $K_t = K_e = 1$, $R_a = 8\Omega$, and $L_a = 1 \text{ H}$. Substituting these into the above equations, and using the state function, a system of matrices is formed. Using the MATLAB state function, the following transfer function emerges:

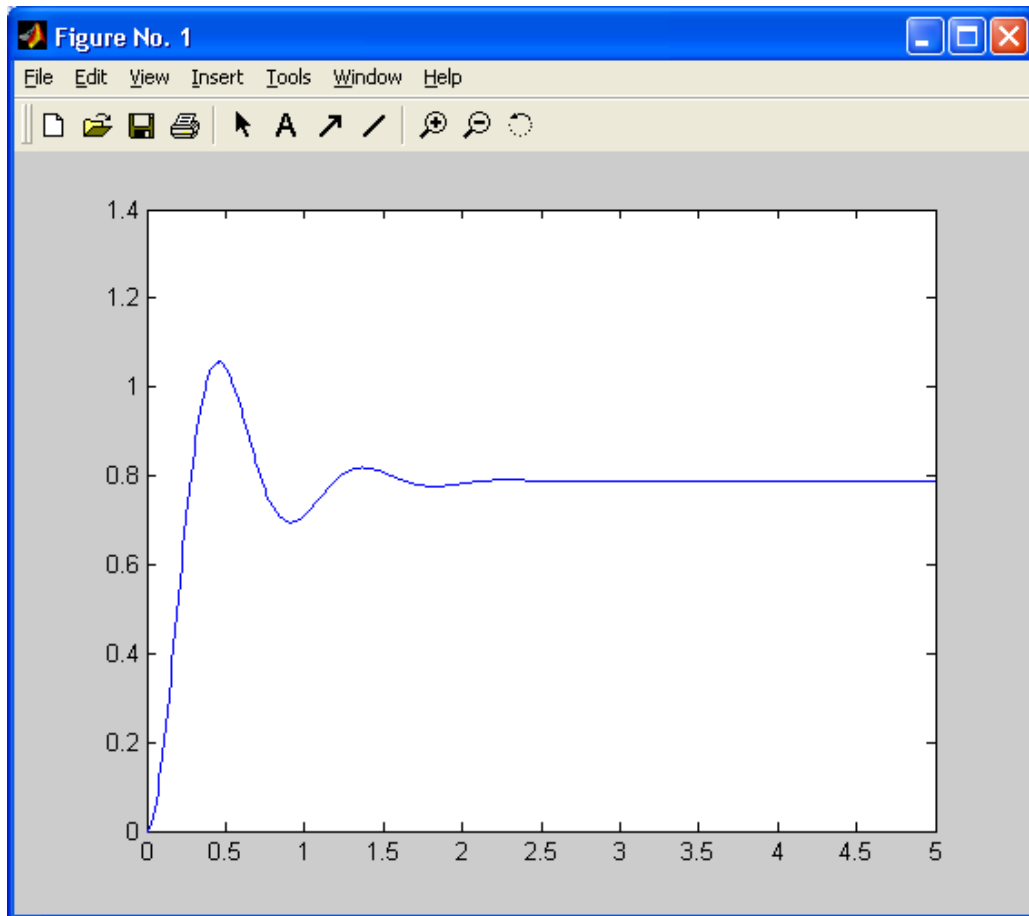
$$G(s) = \frac{100}{2.4s^2 + 11.3s + 127} \quad (\text{Eqn 6})$$

Now that the transfer function has been established, it can be entered into MATLAB to simulate the response of the motor to constant load. This was done using the code below:

```
numb = [0 0 100];           % Inputs numerator
denb = [2.4 11.3 127];     % Inputs Denominator
sysb = tf(numb, denb);     % Defines Transfer Function
t = 0:0.01:5;              % Sets time step vector
y = step(sysb,t);          % Finds step response
plot(t,y)                  % Plots step response versus time
```


The plot produced shows how the motor will respond to the control box. The rpm of the motor was not taken into account, thus making the plot dimensionless. It could, however, be taken into account and the plot adjusted accordingly.

Figure 8: MATLAB plot of control box response to motor. The x-axis represents time and the y-axis represents power to the motor via rotational velocity.

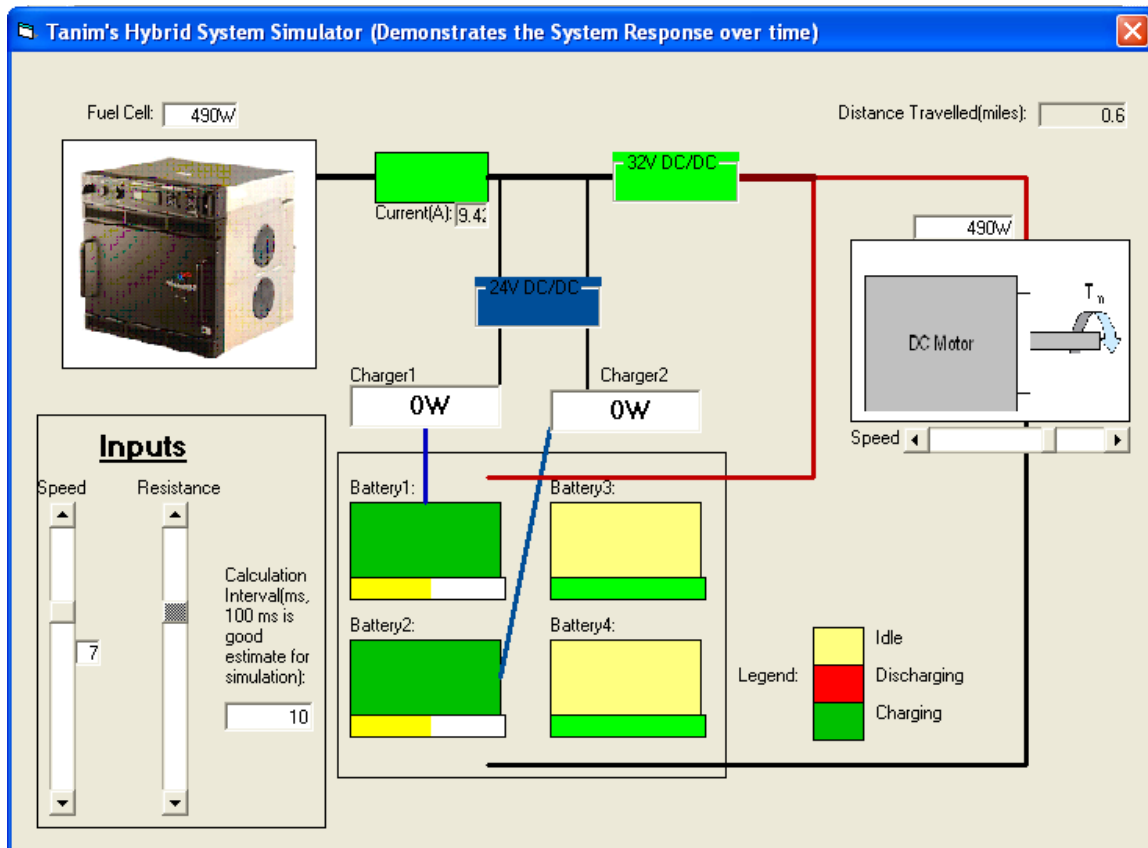


The function response is what would be an ideal output from the control box. The sinusoidal plot shows that the system responds quickly enough to avoid a massive overshoot, but quickly enough to stabilize in just over a second. The capacitor placed before the motor will help to dampen the overshoot as well.

4.4.6.2. The Visual Basic Simulation

A screen-dump of the simulation program is shown below:

Figure 9: Screenshot of simulation program



Objective

The objective of this program was mainly to simulate how the control circuit would respond to various parameters: both external (terrain friction, weight of passenger) and internal (battery charge, fuel cell and motor power parameters), and driver's input.

Program Usage Instruction

Operating the program is very simple: just move the two sliders in the 'Input' box. The calculation time interval specifies in milliseconds, the time interval between each

calculation cycle. 100ms would give an overall simulation that should closely simulate the time cycle of the real system when it is built.

Output Parameters

The outputs are the various wattage readings for the different components: fuel cell, motor, charger, etc. This is very important from a design perspective as it lets the designer change circuit settings based on suitable power values obtained from the simulation. From the vehicle rider's point of view, the distance traveled and the speed of the vehicle forms the second output set.

Most important to the system designer, the program shows the connections that are being made and broken using a simple, but powerful visual interface.

Modeling

For this purpose, basic models had to be designed for the electric motor, the fuel cell, the charger and the batteries. Due to inadequate data about these components, fairly simple models were chosen.

- a) The charger had the simplest model: simply as a component which took in 0/125/250 watts of power depending on mode of operation. It is assumed to be 50% efficient, i.e. 50% of energy going into the charger is assumed to be stored into the battery.
- b) The charge controller was more complicated since it has to switch between the batteries in order to maintain charge balance between the two batteries in each pair that is in series. Overcharging and under-charging also had to be taken into account, in deciding which pair to charge. Now, the lifespan of a lithium ion is cut short if it goes through rapid charging and discharging cycles. In order to prevent this, the charger controller charges a pair in series until it is at least 80% charged, and prevents it from being discharged during this period.
- c) The fuel cell model is also quite simple. It simply calculates the power going out.
- d) The battery is simply modeled by the amount of stored energy that is represented graphically. The lithium ion batteries can handle large currents, and so this model is suitable.
- e) The electric motor, by far had the most complicated model. It's power demand depends on its rotational velocity, the resistance to motion it has to counter, and the supplied and back emf voltages.

Results

- a) In the real system, the fuel cell would shut down if the current exceeds 10 Amps. In the simulation program, careful observation shows that the current does not exceed 10A and therefore the fuel cell does not need to shut down. Additionally, the power demand on the fuel cell is seen to be mostly maintained at 400-500 watts (or 0 watts when both battery pairs are charged), meaning the load on the fuel cell is mostly constant. This was the main objective of the hybrid control circuit.
- b) The program shows how the charge controller in the real system should switch between the batteries and the charging modes. The controller maintains charge balance and keeps the system supplied for handling spikes in power demand.
- c) Overall, the simulation shows that the vehicle could theoretically keep running continuously until the fuel cell's hydrogen has all been consumed (hydrogen consumption has not been added to the simulation, but it is a simple matter to do so).

4.4.7. Conclusion

Summary of Work done by Hybridization Team

We in the hybridization team had hoped to build a working hybrid system by the end of the semester. Although a hybrid schematic has been designed, implementing the fully hybrid system would have required more time than we had available. We had also hoped to simulate the full schematic, but again, due to time, we could only do part of it. Nevertheless, we are very pleased about the extraordinary progress that has been made in regards to hybridization. We have:

- a) Documented how to use the laboratory equipment. This should help any person joining the project get up-to-speed without facing the problems and delays that we had to face due to lack of information regarding their operations.
- b) We have provided the specifications for and have been in constant contact with Microsun in regards to the development of a charging system.
- c) The team has designed a circuit to go with these chargers, and have ordered necessary parts for its implementation.
- d) The implementation of this circuit is very complicated due to the vast number of connections. However, concrete steps have been taken in order to achieve the implementation.

- e) A hybrid system was designed and its functioning well documented. The circuit is based mostly on the parts that we already have and so its implementation should be fast.

Implications

The major implication of our work is that we have been able to show that even low power fuel cells can be used for a wide range of applications, even for the complicated process of powering an electric vehicle. Concerning lithium ion batteries, we have shown that they can be used in electric vehicles too.

More work is still left to be done before the electric vehicle can be called a 'hybrid'. However, the next team working on this project will find it useful to have a charger and many other parts. Then, after perfecting the hybrid design, they can implement the hybrid system quickly due to the fact that many parts are re-used in the design.

Next Steps

The following are the immediate future objectives in regards to hybridization. That is, the next team working on the project should:

1. Simulate the theoretical hybrid system and modify its design accordingly
2. Based on the simulation results, examine the feasibility of the hybrid system
3. Obtain necessary parts and implement

4.5. Vehicle Design

The vehicle design team was assigned the task to construct and modify the wheelchair and auxiliary trailer. At the beginning of the project the vehicle had already been modified by the previous IPRO team by the removal of the original lead-acid batteries and the addition of a trailer hitch to attach the auxiliary trailer to the wheelchair. The auxiliary trailer had been modified by the installation of a platform to allow the attachment of the fuel cell, hydrogen cylinders and battery packs. In order to perform more efficiently the auxiliary trailer needed to be greatly improved while the junction between the trailer and the wheelchair needed to be redone. Further in order to increase the safety and comfort for the driver a new seat post had to be created.

4.5.1. Seat and Devises

Our first object was to improve the current seat mounting system and to install all the necessary equipment (fuel cell, hydrogen cylinders, switches and battery packs) onto the trailer in an efficient and safe manner. Our team's first concern was to make the trailer strong enough to mount the various devises. During an initial test run with the wheelchair and trailer it was found that the current trailer would not be sufficient of the needs of this IPRO. It further could not meet the safety requirements as one of the wheels unscrewed itself during the test run due to an engineering flaw of the trailer itself. It was therefore necessary to find a new trailer that would be strong enough to hold the heavy fuel cell, a hydrogen tank and eight lithium ion batteries. A new trailer was found that was more flexible than the old trailer as it allowed a more flexible arrangement of the various devises on the trailer. It was also lighter than the previous trailer and provided the necessary design elements to provide an easier attachment to the wheel chair.

The seat mounting system that was provided on the wheel chair at the beginning of the semester was essentially a lawnmower seat attached to a metal rod by means of a screw. The reason why the original wheelchair seat had to be removed was because of weight issues. The seat that was provided with the wheelchair was very luxurious and had a considerable weight. It was in the interest of the team to minimize the weight of the wheelchair to increase the mile per liter of hydrogen and therefore the seat needed to be replaced. Given the seat post design it was found necessary to find a more stable way to attach the seat. Currently the seat had to many degrees of freedom hand became uncomfortable to sit on for longer periods of time due to the high degree of freedom in all directions. Our team therefore created an entirely new seat post that now provides a very comfortable seating opportunity and is considerably more stable.

Figure 10: New seat mounting system



While mounting the various devices on the new trailer concerns arose that the board that was the bottom of the trailer would not be stable enough to sustain the weight of all the devices that would be put on the trailer. After doing some testing it was found that this wasn't an issue and therefore the team proceeded to mount the fuel cell, the batteries and hydrogen tank onto the trailer. In order to ensure that these devices would not be able to slide off the trailer angles were used along the sides of each device. These angles includes slits on their sides so it would be possible to strap down all the devices would it be necessary. Further using angles that are simply screwed onto the wooden floor it would be easily possible to rearrange the devices on the trailer would it be necessary.

Figure 11: Metal support angles



4.5.2. Connection Trailer - Wheelchair

After all the devices were safely mounted onto the trailer a solution needed to be found how the trailer would be attached to the wheelchair which lacked any pre-manufactured means to attach trailers to as it was meant to be used as a stand along vehicle. As no system was present it was necessary to design an attaching system that would be compatible with both the wheel chair and the trailer. This was done by installing a ball-hitch to allow for a quick removal of the trailer if necessary.

Figure 12: Ball-hitch for connection between vehicle and trailer



4.5.3. Safety Improvements to Design

In order to test the current system a test run was performed using the design and no problems were found with the trailer after the first test drive. An improvement to put the batteries on the wheelchair instead of the trailer was recommended in order to decrease the amount of cables running across the connection between the trailer and the wheelchair. By putting the batteries on the wheelchair it would further reduce the weight on the trailer and would leave more room on the trailer for more hydrogen tanks and for components that the hybrid circuit would need.

Next to the rearrangement of the battery packs an improved method to safely attach the hydrogen tank to the trailer was found. Using two worm-drive clamps and a slit rubber tube would allow a very stable attachment of the hydrogen cylinder to the trailer but would not significantly reduce the time required to remove and replace a hydrogen tank.

Figure 13: Hydrogen Tank Attachments



Further in order to ensure the safety of the driver of the vehicle the two battery packs were shielded using fire protective measures. The reason for this was lithium-ion batteries have the potential of becoming hazardous if they are improperly used. Despite various safety measures included in the circuits themselves it was concluded that it is smarter to put safety first and include additional protection in the case that fire would start inside the batteries packs, even though this risk was considered very small.

4.5.4. Pictures of Vehicle

The following pictures show the wheelchair and its trailer.

Figure 14: Wheelchair



Figure 15: Trailer with Equipment



4.6. Business

4.6.1. 100 – Mile Drive

4.6.1.1. Plan for the 100-mile Drive

The initial objective of this IPRO was to drive the fuel cell powered people transporter, or motor scooter, for 100 miles from Chicago to Milwaukee. However evaluation of the laws in Illinois and Wisconsin proved the drive an unsafe and costly endeavor. It was found that a motor scooter, such as the one used in the people transporter could only be driven on sidewalks with proper registration with each district it is to be driven in and it could not be driven on roadways, bike paths, or walking trails.

With the approval of the sponsors, the IPRO 304 team decided it was in the best interest of the safety and legality of the project to limit the 100-mile drive to an on-campus route at IIT or to make laps around the parking lot at US Cellular field adjacent to the IIT campus. Both routes are relatively level courses, which makes for an even power requirement of the transporter. The transporter is equipped with an odometer to measure the distance traveled. The laws and safety concerns of the motor scooter are explained in the following sections.

4.6.1.2. Legal Aspects

Several laws are of concern when considering hydrogen transport and the operation of motor scooters like the one utilized in this IPRO. Since the planned route involved traveling a long distance through Northern Illinois, motor scooter operation on public roadways was considered. Under Illinois statute 625 ILCS 5/11-1403.5 of the Motor Vehicle Code, it is not legal to operate motor scooters on roadways or sidewalks without proper approval by local jurisdictions. Because original route plans involved riding through multiple municipalities in Illinois the approval process is potentially costly, time consuming, and beyond the focus of this project.

Another consideration was the safety of transporting hydrogen on the cart. Under 49 CFR (100-800), the federal Hazardous Materials Regulation code followed by the DOT and Hazmat, hydrogen is considered a flammable compressed gas (class 2.1). All cylinders must be ANSI approved compressed gas cylinders and must be labeled with the proper chemical name, "Flammable Gas," "Portable Tank," and the international identification number, UN1049. Cylinders must be transported on a suitable-frame vehicle, with a flat floor or platform. The cylinders must be securely attached to the frame to prevent any movement, including any contact with other cylinders. Cylinders cannot be stacked and must be stored vertical, unless

designated as a horizontal-mount cylinder. Although the hydrogen used for the transporter was in the form of compressed gas it is recognized that special codes exist for the transport of cryogenic liquid hydrogen.

State codes require that all transporters of hydrogen and hazardous materials must obtain a state permit and refer to the 49 CFR codes. Chicago fire codes follow the Nation Fire Protection Agency codes 50A and 50B. However, neither of those codes applies to hydrogen systems involving cylinders with volumes less than 4CM (11CF). While all of these codes apply to the transport of hydrogen on roadways, the motor scooter is not a road-safe vehicle. The interpretation of these codes in reference to the people transporter is undefined and all codes should be followed to the best of their interpretation for the safety of the project.

There are no existing codes of laws for the use of fuel cell powered vehicles or the use of hydrogen as a commodity fuel. A task force largely consisting of ASME and ANSI members is presently developing an international set of codes for the use of hydrogen as a fuel and for fuel cell powered vehicles.

4.6.2. Safety and Health Risks of Hydrogen Fuel

Despite claims that hydrogen is a hazardous and unsafe for vehicle use, it is no more dangerous than gasoline or methane. The flammability limits of hydrogen, 4.1-74.0%, are much larger than gasoline, 1.4-7.6%, and methane, 5.3-15%, but hydrogen dissipates quickly in open spaces due to its low density, reducing risks for reactions and ignitions. A hydrogen fire emits one-tenth the heat of a gasoline fire, and the explosive power of hydrogen is 22 times weaker than the explosive power of gasoline.

Hydrogen is highly flammable and can react violently with oxidizers, such as oxygen, in constrained volumes. The major health hazard of hydrogen is thermal burns from fires. Hydrogen is non-toxic but may cause asphyxiation in enclosed environments. Hydrogen flames are clear or light blue, which often are not visible to the eye. If a fire does start, the only way to extinguish it is to cut off the supply. The major health hazard of hydrogen is thermal burns from fires.

Environmental Factors

Hydrogen fuel cells are highly appealing to environmentalists because they produce little carbon emissions, no sulfur emissions, and little or no nitrous oxide emissions. Conventional gasoline combustion engines in vehicles produce 130 gm of carbon emissions per mile, while fuel cell powered vehicles produce 49-57 gm of carbon emissions per mile. This is a substantial decrease in the carbon emissions and supports the appeal of fuel cell powered vehicles. Also, 1 kg of hydrogen

contains the same amount of energy as 2.1 kg of natural gas and 2.8 kg of gasoline. Hydrogen fuel cells utilize this energy with 60% efficiency, compared to gasoline combustion engines that are 18-20% efficient.

Production of hydrogen has increased by 23 percent between 1994 and 1999. Current hydrogen consumption is almost entirely by industry, i.e. oil refining, petrochemical production, electronics, rocket fuel, and food processing, but NASA currently uses hydrogen as an energy carrier. Current production of hydrogen is through fossil fuels; long-term production will be largely derived from renewable resources, i.e. water and solar energy, to meet a growing demand to reduce or eliminate fossil fuel consumption.

4.6.3. Cost of Transporter

As we know today the cost of Hydrogen is far more expensive than the cost of gasoline. Having a fully hybridized system has its advantages, but until the cost to produce and distribute hydrogen comes down gasoline will continue to be the number one source of fuel in the world.

4.6.3.1. Description of Program

The business team decided to create a program that people will be able to use to keep track of major parts and materials use to create hybrid system for the wheelchair. The program also calculates and compares the cost of operating our hybrid vehicle vs. a gasoline vehicle. The program is written in C++. Once in the program the user has multiple options to choose from. Future IPRO's will be able to make changes to the code to make it more efficient for there own use and user of the program. Below are the list of options the user can select and there functionality:

- R: read in file
- +: add a new entry
- : remove an entry
- D: display entire file
- W: write to a file
- P: select a part number
- N: select a part by name
- C: calculate price
- \$: determine operation cost
- Q: quit the program

R: read in file – If user type 'R' or 'r' at the command line a file will be read into the program. The file will list major parts associated with the Hybrid Fuel Cell People Transporter. Along with the name of the part the file will list a manufacture if information was available to us, a part number created by the business team, and the quantity of the listed part. The part number and quantity are on the same line. This was done more to preserve space. The way the program was written, if every entry had its own line the program would have a very extensive display of our list. The fourth and final line of the file holds the cost of the particular part. Being that this is an IPRO we did not have to make to many major purchases. Some of the parts listed may not have a price associated with it for various reasons. Some of those reasons are as follows: part may have been donated to the University by a student, faculty member, or corporation; part may have already been in IIT's inventory and made accessible for our class to use; part may of been used in previous semesters and there is no record of it cost. Although items such as the fuel cell and motorized wheelchair were donated to the University their prices are listed based on market value. This option will also inform user of total cost associated with the parts listed in the file and the number of entries listed.

+: add a new entry – If user types '+' at the command line they will be able to add an entry to the parts list file. User will be prompted to enter a new part, manufacture (if available), part number, quantity, and finally a cost for the part (if available). Entry will be added to the end of the file in the same format as the entries already listed on file. Once complete the entry count will be +1 and the new part count will be displayed.

-: remove an entry – If user types '-' at the command line they will be able to delete an item for the parts list file. The only way to delete and item is by knowing the part number. If part number is unknown then user will have to look up part number from within the program or by means outside of this program. Once part number is entered and enter is pressed the part is deleted from the list. The total number of entries in file will be -1 and the new total will be displayed.

D: display entire file - If user types 'D' or 'd' at the command line the entire file will be displayed. Each part will be listed followed by the manufacture, then the part number and quantity, and finally the cost of the product. Each entry will be separated by a space bar. Can use display option to view each line item, to see how part was entered into the file, or to find out part number.

W: write to a file – If user types 'W' or 'w' at the command line the user can save entry. User will have the option to save entry in exiting file or create a new filename that would like to refer to later. Once file is save user can then go to the location of folder the file is found in a print file if needed.

P: select a part number – If user types 'P' or 'p' at the command line they will be able to look up a part with its part number. The user will be prompted to enter the part

number associated with particular part and all data on part will be displayed, name of part, manufacture, part number, quantity, and cost.

N: select a part by name - If user types 'N' or 'n' at the command line they will be able to look up a part with its name. The user will be prompted to enter the name of the part and all data on part will be displayed, name of part, manufacture, part number, quantity, and cost. If name is not listed as it is on the file part will not be displayed and user will get an error message. If user doesn't know how the item was entered into the file they can use display option to view entire list.

C: calculate price – If user types 'C' or 'c' at the command line they will be able to see the total prices associated with the Hybrid Fuel Cell People Transporter. Of course if the cost is zero then the cost of that particular part is not included in the total price. Unfortunately the program was written to only calculate the cost of one item per part number. When user enters a new entry if it has a quantity of 5 users will need to enter the total cost of all 5 items.

\$: determine operation cost – If user types '\$' at the command line they will be able to calculate the cost of operating our vehicle compared to gasoline pricing. User will be prompted to input own pricing values or they may use the values hard coded into the program. If the chose to input values the will be asked to enter the cost of gasoline and then the cost of hydrogen. User will also need to input the number of miles they desire to travel. Program calculator will then determine the average cost of the trip using each fueling method. If the user opts for the second method to have the program generate the cost of a trip, the user will be instructed to enter number of mile desired to travel. The values to calculate cost of each fuel method are the following: \$2.05 per gallon for gasoline and \$1.36 per pound for hydrogen.

Q: quit the program – If user types 'Q' or 'q' at the command line they will be able to quit this program.

4.6.3.2. Parts List and Costs

Table 4: List of Major Parts and cost

ITEM	Cost/ea.	Actual/estimated	Quantity
Electric wheel chair	\$3000	Cost estimated. Item was donated	1
Li-ion batteries	\$50	Estimated based on items used	8
Passive cooling system	-		1
Fuel cell	\$2000	Cost estimated. Item was donated	1
Hydrogen tanks	\$150	Estimated	1
Hydrogen sensor	\$1100	Estimated	
Hydrogen connectors	\$70	Estimated	
Trailer	-		1
Seat	\$100	Estimated	1
Ratcheting canvas straps	-		
power relay	\$6	Actual	25
rail/screw terminal sockets	\$7	Actual	25
Aluminum Chassis	\$29	Actual	1
Chassis Cover Plate	\$10	Actual	1
Pin female D-SUB sockets	\$2.5	Actual	14
D-SUB 2m cable	\$5	Actual	14
DC/DC converter	\$199	Actual	2

Table 5: Parts that make up Batteries

ITEM	Cost	Actual/Estimated	Quantity
Safety circuits	\$27	Actual	6
Plexiglas	-		-
Wire leads	-		2
Individual lithium-ion cells	-		24
Gage wire	-		18
Paraffin wax	-		240g
Aluminum foam block	-		1

4.6.3.3. Comparison between other Fuel Sources

Hydrogen vs. Gasoline

The projected fuel cost for a hydrogen-fueled automobile is estimated at 3.8 cents per mile vs. 4.5 cents per mile for one powered by gasoline. The average gasoline price of \$1.95 per gallon and an average price of \$1.27 per pound of hydrogen. The comparison, which excludes federal or state taxes on hydrogen, takes into account the average propulsion efficiency of internal combustion engine-powered vehicles, which is about 15 percent, vs. 50 percent efficiency for a vehicle powered by a fuel cell.

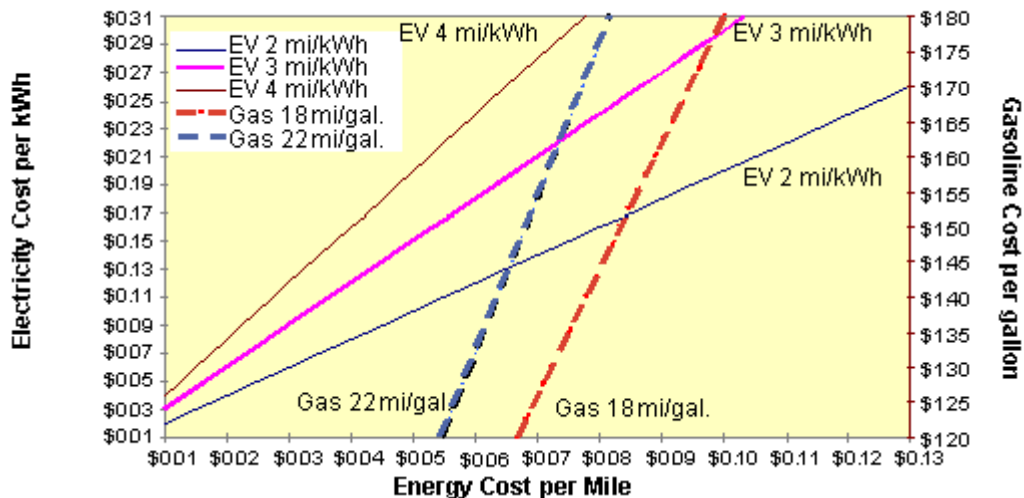
Expected Cost and Efficiency Improvements for 5kW Stationary Fuel Cells (2002 – 2010)

	2002	2004	2010
Fuel Cell Cost (5kW)	\$50,000	\$15,000	\$3,000
Efficiency	30%	35%	45-60%

Source: Fuel cell industry interviews

Energy vs. Gasoline

Energy cost is another area where it is possible to reap economic benefits by utilizing electric vehicles. The fuel cost of driving an electric vehicle depends on the cost of electricity per kWh and the efficiency of the vehicle. To determine the cost per mile of an electric vehicle using the graph below, select the location on the left axis (Electricity Cost per kWh) at 7 cents in the graph below. Draw a horizontal line to the right until you bisect the EV 3 mi/kWh line. Next draw a vertical line down until you intersect the bottom axis (Energy Cost per mile). This indicates that the fuel for an electric vehicle with an energy efficiency of 3 mi/kWh cost about 2.3 cents per mile when electricity cost 7 cents per kWh.



Currently, the national average cost for electricity is about 6.8 cents per kWh, while the average residential rate is around 8.5 cents per kWh. Some electric utility companies have special rates in place that are cheaper at night when the demand for electricity is low. These rates can be as low as 3 cents per kWh. Older electric vehicles in commercial fleets have energy efficiencies of about 2 mi/kWh while new electric vehicles such as GM's EV1 have energy efficiencies of over 6 miles per kWh. Heavy duty vehicles such as trucks and buses average about 1 mile per kWh.

Older less energy efficient electric vehicle(2 mi/kWh) at the national average of 7 cents per kWh, is cheaper to operate at 4 cents per mile than the more efficient(Gas 22 mi/gal) vehicle operating with the national average of \$1.25 per gallon at over 7 cents per mile.

4.7. Website

When this project began, a set of objectives were set by the team leader which were to be completed by the end of the semester. These tasks involved the following: gaining full access from the OTS to the existing website, redesigning the main layout of the website, creating a site which incorporated information from the old site and current information from this semester's group, making three movies available on the website from last semester's CD, creating detailed documentation of the webpage, and making important documents available online as soon as they were received. During the first week, the team was able to contact the CNS, request a password change, and with written permission from Professor Al-Hallaj, was able to completely gain access to the site. After gaining full access a URL redirect for our current site (<http://ipro304f04.no-ip.com>) was created. This was done by visiting <http://www.no-ip.com>, setting up a new account, registering the redirect URL for the site, and then activating it.

The next thing which was completed was the overhaul of the existing website, which was performed by designing some white sheets of possible layouts and which content from the old site would be included with the new one. Once a design was selected and approved by the team, the team designed it using Adobe Photoshop 7.0, which took about three days to complete. Once the design was finished, it was exported from Photoshop and began the actual HTML work in Microsoft FrontPage 2003. This was a rather a quick task since all that was needed to be done was to begin typing in the information and setting up some links. The process which took a fair amount of time was compiling the spring 2004 accomplishment's page which involved retrieving documents from Yahoo! Groups, sifting through them and selecting information to add. Extra information which was included was the resources section, upon the request of our team leader, which included links to sites which provide a simplified explanation of how a fuel cell works. Within the pictures and videos section, videos and pictures were uploaded via FTP from the IPRO CD and from Yahoo! Groups.

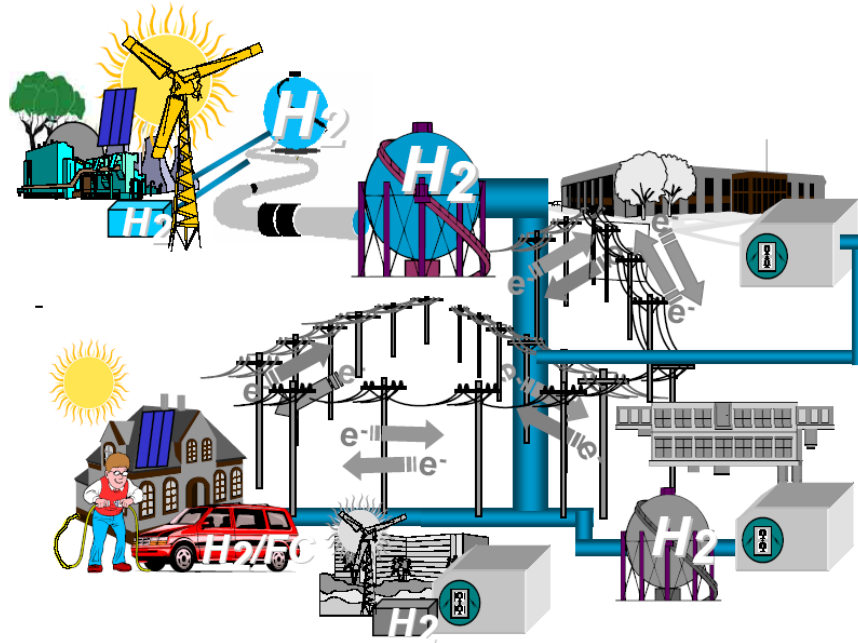
The only problem, which reoccurred throughout the project, was space limitations, which was quickly fixed by having Professor Al-Hallaj write an email to the CNS department, approving quota increases. The safety section was added to store links to various documents pertaining to the safe handling and operation of hydrogen. The team section stated the objectives of each team and their members; the sponsors section contained links to our sponsors, except for *All Cell Technologies* as no existing company website was found; the hardware section contained specifications to our hybrid scooter; and the future goals section which contained the future goals of each team. In order to display news more professionally, a java applet was created to display news and upcoming events on the front page from an XML file located in a folder on the web server. The only suggestion which was brought up by a member of the group was to create a dot com

address (e.g. <http://www.ipro304.com>) for the site which would simplify the navigation process to the site.

Throughout this process, time management was an absolute necessity in order to maintain on task and still produce quality results. Throughout this project it was possible to gain a better idea of how real businesses operate and the importance of managing ones time in order to meet deadlines and complete goals quickly to have the ability to check ones work and control the quality of the end product.

5. Hydrogen Economy and the Future

5.1. Overview of the Hydrogen Economy



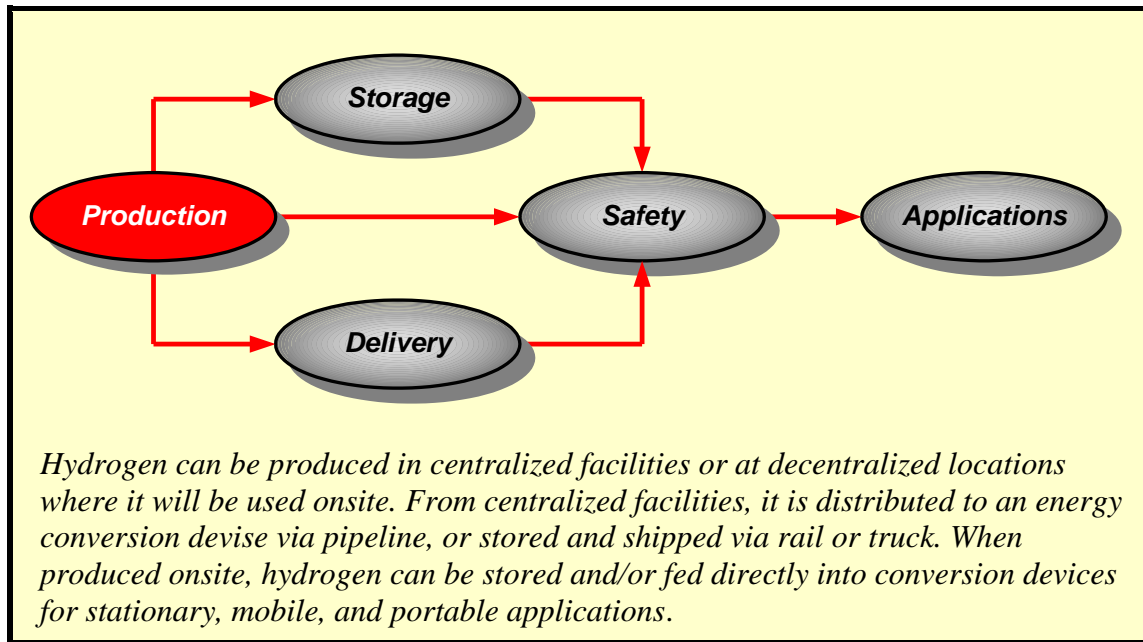
5.1.1. Introduction

We are focusing on next generation technologies that expand the diversity of America's supply of energy and "leap frog" the status quo. This requires a revolution in how we find, produce, deliver, store, and use energy. Hydrogen represents a potential solution to America's needs. To talk about "the hydrogen economy" is to talk about a world that is fundamentally different from the one we know now. A hydrogen economy will mean a world where our pollution problems are solved and where our need for abundant and affordable energy is secure...and where concerns about dwindling resources are a thing of the past.

Widespread use of hydrogen will affect every aspect of the U.S. energy system, from production through end-use. The individual segments of a hydrogen energy system – production, delivery, storage, conversion, and end-use applications – are closely interrelated and interdependent. Design and implementation of a hydrogen economy must carefully consider each of these segments as well as the "whole system".

This paper contains no original work; it is a compilation of existing published reports detailing the economics of hydrogen technologies.

5.1.2. Production



Hydrogen can be produced from a variety of sources, including fossil fuels; renewable sources such as wind, solar, or biomass; nuclear or solar-powered thermonuclear reactions; and solar photolysis or biological methods. The current United States hydrogen production is for use in chemicals production, petroleum refining, metals treating, and electrical applications. Although hydrogen is the most abundant element in the universe, it does not naturally exist in large quantities or in high concentrations on Earth – it must be produced from other compounds such as water, biomass, or fossil fuels. Various methods of production have unique needs in terms of energy sources (e.g., heat, light, electricity) and generate unique by-products or emissions.

Between 55-60% of the hydrogen being produced in the world today is produced by steam reformation. Hydrogen is also produced via water electrolysis using electricity from the existing power grid. Coal and nuclear are possibilities as are solar technologies, including solar photovoltaic, and solar thermal power. Wind is also an option. Advanced technologies like photochemical, photoelectric chemical, and thermal chemical – the high temperature processes where solar thermal seems like an ideal source – are also under development.

5.1.2.1. Hydrogen Production Technology

Three distinct types of commercially proven technologies are available to extract hydrogen from feedstocks. Fundamental principles for each technology apply regardless of the unit size. A brief review of reforming, gasification, and electrolysis describes the major processing steps required for each hydrogen production pathway.

- Reforming is the technology of choice for converting gaseous and light liquid hydrocarbons.
- Gasification or partial oxidation is more flexible than reforming – it could process a range of gaseous, liquid, and solid feedstocks.
- Electrolysis splits hydrogen from water.

5.1.2.1.1. Reforming

Steam methane reforming (SMR), methane reforming, and gasoline reforming are based on the same fundamental principles with modified operating conditions depending on the hydrogen-to-carbon ratio of the feedstock.

SMR is an endothermic reaction conducted under severe conditions; the typical operating conditions are 30 atmospheres and temperatures exceeding 1,600°F. Conventional SMR is a fired heater filled with multiple tubes to ensure uniform heat transfer.



Typically the feedstock is pretreated to remove sulfur, a poison that deactivates nickel-reforming catalysts. Guard beds filled with zinc oxide or activated carbon are used to pretreat natural gas and hydrodesulfurization is used for liquid hydrocarbons. Commercially, the steam to carbon ratio is between 2 and 3. Higher stoichiometric amounts of steam promote higher conversion rates and minimize thermal cracking and coke formation.

Because of the high operating temperatures, a considerable amount of heat is available for recovery from both the reformer exit gas and from the furnace flue gas. A portion of this heat is used to preheat the feed to the reformer and to generate the steam for the reformer. Additional heat is available to produce steam for export or to preheat the combustion air.

Methane reforming produces a synthesis gas (syngas) with a 3:1 H₂/CO ratio. The H₂/CO ratio decreases to 2:1 for less hydrogen-rich feedstocks such as light

naphtha. The addition of a CO shift reactor could further increase hydrogen yield from methane from SMR according to Equation 2.



The shift conversion may be conducted in either one or two stages operating at three temperature levels. High temperature (660°F) shift utilizes an iron-based catalyst; whereas medium and low (400°F) temperature shifts use a copper based catalyst. Assuming 76% SMP efficiency coupled with CO shift, the hydrogen yield from methane on a volume is 2.4:1.

There are two options for purifying crude hydrogen. Most of the modern plants use multi-bed pressure swing adsorption (PSA) to remove water, methane, CO₂, N₂, and CO from the shift reactor to produce high purity product (99.99%+). Alternatively, CO₂ could be removed by chemical absorption followed by methanation to convert residual CO₂ in the syngas.

5.1.2.1.2. Gasification

Traditionally, gasification is used to produce syngas from residual oil and coal. More recently, it has been extended to process petroleum coke. Although not as economical as SMR, there are a number of natural gas-based gasifiers. Other feedstocks include refinery wastes, biomass, and municipal solid waste. Gasification of 100% biomass feedstock is the most speculative technology being developed. Total biomass based gasification has not been practiced commercially. However, a 25/75 biomass/coal has been commercially demonstrated by Shell at their Buggenm refinery. The biomass is dried chicken waste.

In addition to the primary reaction shown by Equation 3, a variety of secondary reactions such as hydrocracking, steam gasification, hydrocarbon reforming, and water-gas shift reaction also take place.



For liquid and solids gasification, the feedstocks react with oxygen or air under severe operation conditions (2,100°F – 2,600°F at 400 – 1,200 psig). In a hydrogen production plant, there is an air separation unit (ASU) upstream of the gasifier. Using oxygen rather than air avoids downstream nitrogen removal steps.

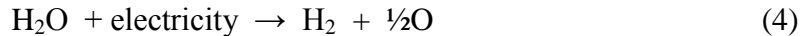
In some designs, the gasifiers are injected with steam to moderate the operating temperatures and to suppress carbon formation. The hot syngas could be cooled directly with a water quench at the bottom of the gasifier or indirectly in a waste heat exchanger (often referred to as a syngas cooler) or a combination of the two. Facilitating and CO shift reaction, a direct quench design maximizes hydrogen

production. The acid gas (H₂S and CO₂) produced has to be removed from the hydrogen stream before it enters the purification unit.

When gasifying liquids, it is necessary to remove and recover soot (i.e., unconverted feed carbon), ash, and any metals (typically vanadium and nickel) that are present in the feed. The recovered soot can be recycled to the gasifier, although such recycling may be limited when the levels of ash and metals in the feed are high. Additional feed preparation and handling steps beyond the basic gasification process are needed for coal, petroleum coke, and other solids such as biomass.

5.1.2.1.3. *Electrolysis*

Electrolysis is decomposition of water into hydrogen and oxygen, as shown in Equation 4.



Alkaline water electrolysis is the most common technology used in larger production capacity units. In an alkaline electrolyzer, the electrolyte is a concentrated solution of KOH in water, and charge transport is through the diffusion on OH⁻ ions from cathode to anode. Hydrogen is produced at the cathode with almost 100% purity at low pressures. Oxygen and water by-products have to be removed before dispensing.

Electrolysis is an energy intensive process. The power consumption at 100% efficiency is about 40 kWh/kg hydrogen; however, in practice it is closer to 50 kWh/kg. Since electrolysis units operate at relatively low pressures (10 atmospheres), higher compression is needed to distribute the hydrogen by pipelines or tube trailers compared to other hydrogen production technologies.

Status of Hydrogen Production Processes

Production Process	Status
SMP of Natural Gas	Mature
Partial Oxidation	Mature
Coal Gasification	R & D / Mature
Water Electrolysis	Mature
Thermochemical	R & D
Photo Chemical Process	R & D
Photo Electric	R & D
Photo Biological	R & D

(Momirian and Veziroglu, 2002)

Steam methane reforming (SMR) accounts for 95 percent of the hydrogen produced in the United States. This is a catalytic process that involves reacting natural gas or other light hydrocarbons with steam to produce a mixture of hydrogen and carbon dioxide. The mixture is then separated to produce a high-purity hydrogen. This method is the most energy-efficient commercialized technology currently available, and is the most cost-effective when applied to large, constant loads. Based on an analysis for NASA completed in 2002, the cost for hydrogen from SMR, without adding any environmental cost on polluting fuels, was estimated at \$6 per gigajoule. Due to rising natural gas costs, today, the estimated cost has increased to \$10 per gigajoule. There are two problems with the SMR process: CO₂ production and the volatile cost of the supply of methane or natural gas – unless methane is going to come from landfills of biomass. If hydrogen is going to come from natural gas, than that cost volatility is troubling.

Partial oxidation (POX) of fossil fuels in large gasifiers is another method of thermal hydrogen production. It involves the reaction of a fuel with a limited supply of oxygen and catalytically converts them to produce a hydrogen mixture, which is then purified. Partial oxidation can be applied to a wide range of hydrocarbon feedstocks, including natural gas, heavy oils, solid biomass, and coal. Its primary by-product is carbon dioxide.

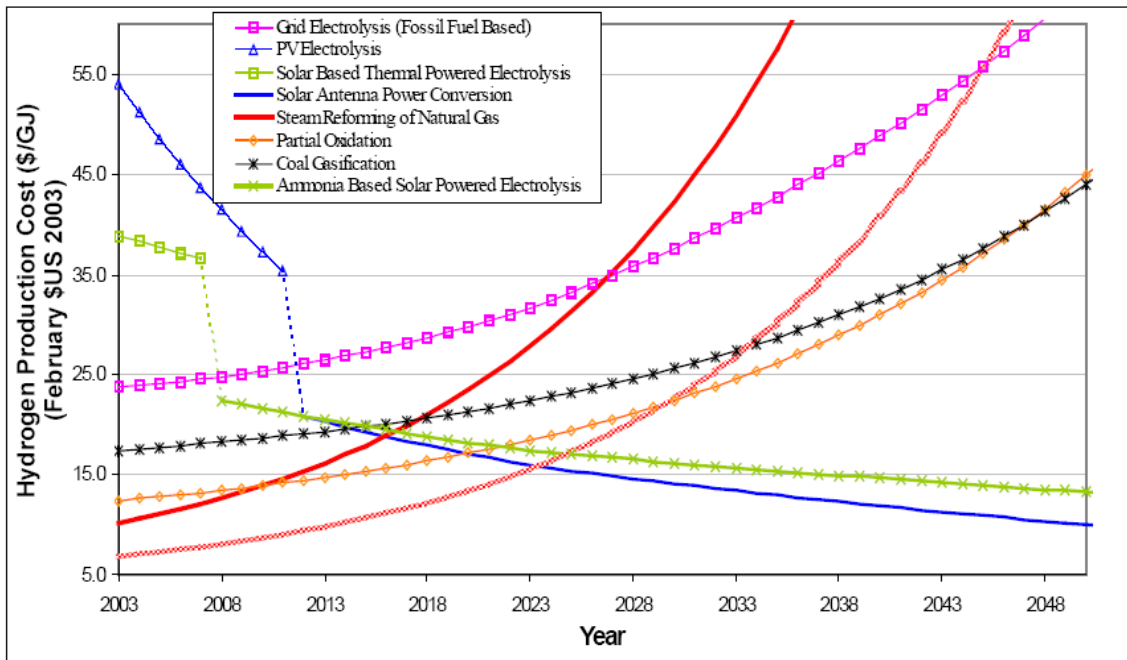
Coal gasification is similar to partial oxidation. However, it can use a wide range of supply of fuels like coal, biomass, and residual oils. This type of plant requires pure oxygen and the coal must be pulverized prior to gasification. It can achieve about 48% efficiency and operates at temperatures around 1,100 – 1,300°C.

Using electricity in electrolyzers to extract hydrogen from water can also produce hydrogen. Currently this method is not as efficient or cost effective as using fossil fuels in steam methane reforming and partial oxidation, but it would allow for more distributed hydrogen generation and open possibilities for using electricity made from renewable and nuclear resources. The primary by-products are oxygen from the electrolyzer and carbon dioxide from electricity generation.

Other methods hold the promise of producing hydrogen without carbon dioxide emissions, but all of these are still in early development phases. They include thermonuclear water-splitting using nuclear and solar heat, photolytic (solar) processes using solid-state techniques (photoelectrochemical electrolysis), fossil fuel hydrogen production with carbon sequestration, and biological techniques (algae and bacteria).

Advance electrolysis technologies work with alkaline water, seawater electrolysis, solid polymer electrolyte, and solid oxide electrolyzer. Seawater is an interesting possibility but it has problems with chlorine and corrosion, which would have to be worked out. Solar-powered electrolysis can be achieved with photovoltaic and solar thermal power. New developments in nano rectenna conversion and combined

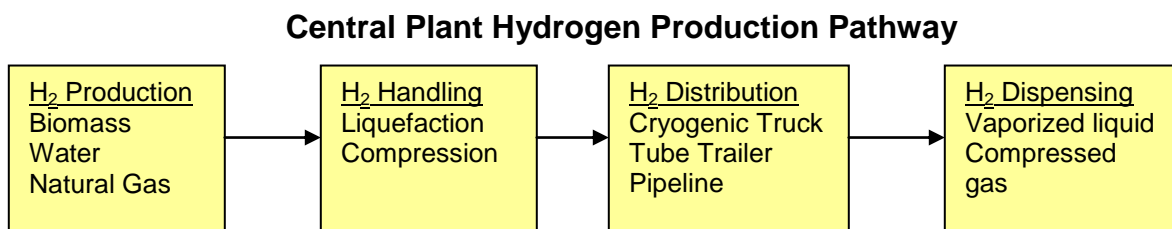
power/cooling cycle are promising. The first two technologies already are available. Costs have come down tremendously over the past two decades and some of the new developments, like nano rectenna conversion and biological photovoltaics, could reduce future costs by orders of magnitude. Any new hydrogen production technology will be compared against steam methane reformation when it comes to commercial investment. The economics of some of these alternatives are compared in the following figure.



This chart shows how the expected hydrogen production cost will increase as the cost for natural gas and the other fossil fuels increase over time. This chart also shows projections of two different solar powered hydrogen production routes. There is an expected step-wise reduction on production costs as the technology develops. Costs based on fossil fuels are going up and the costs based on renewable energy production are going down. In fact, the cost for steam methane reformation has gone up within the last six months. This analysis does not include any environmental penalty for fossil fuels, although one could argue that there is about \$15 per gigajoule in environmental costs when you use coal as a feedstock, about \$13 per gigajoule when you use petroleum as feed stock, and about \$9 per gigajoule when you use natural gas.

5.1.2.2. Central Plant Hydrogen Production

The following figure shows that each central hydrogen pathway consists of four steps: production, handling, distribution, and dispensing.



The following table lists the feedstocks and utility costs used. Central plant production benefits from lower industrial rates, whereas the fueling stations are charged with the higher commercial rates.

Central Hydrogen Production Feedstock and Utility Costs

	Unit Cost
Natural gas (industrial)	\$3.50/MMBtu HHV
Electricity (industrial)	\$0.045/kW
Electricity (commercial)	\$0.070/kW
Biomass	\$57/bone dry ton
Coal	\$1.1/MMBtu dry HHV

Source: Annual Energy Outlook 2002 Reference Case Tables, EIA

The design production capacity for each central plant ranges from 20,000 kg/d to 200,000 kg/d hydrogen with a 90% utilization rate. An arbitrary design capacity of 150,000 kg/d was chosen for the discussion. The following table shows that the cost of hydrogen for hydrocarbon based feedstock is lower than renewables. For each feedstock, the cost of hydrogen via cryogenic liquid tanker truck delivery pathway is 10-25% lower than that by tube trailer and 15-30% less than by pipeline. Since the cost of liquid delivery is relatively small (less than 5%), the cost for hydrocarbon based feedstock, production, and fueling account for close to 67% and 33% of the total hydrogen costs, respectively. For renewables (biomass and water), the production cost accounts for 70-80% of the total hydrogen cost. With high investment costs, the tube trailer and pipeline delivery account for 50% of the total cost.

This chart also shows that the production costs are affected by the delivery method of choice. This increase is due to the additional compressor costs incurred from low pressure pipeline transportation to high pressure tube transport to liquefaction of the hydrogen for tanker transport.

Summary of Central Plant Based Hydrogen Costs
(1,000 kg/d hydrogen)

Delivery Pathway	Liquid Tanker Truck, \$/kg	Gas Tube Trailer, \$/kg	Pipeline, \$/kg
Natural Gas			
Production	2.21	1.30	1.00
Delivery	0.18	2.19	2.94
Dispensing	<u>1.27</u>	<u>1.00</u>	<u>1.07</u>
Total	3.66	4.49	5.91
Coal			
Production	3.06	2.09	1.62
Delivery	0.18	2.09	2.94
Dispensing	<u>1.27</u>	<u>1.00</u>	<u>1.07</u>
Total	4.51	5.18	5.63
Biomass			
Production	3.53	2.69	2.29
Delivery	0.18	2.09	2.94
Dispensing	<u>1.27</u>	<u>1.00</u>	<u>1.07</u>
Total	4.98	5.78	6.30
Water			
Production	6.17	5.30	5.13
Delivery	0.18	2.09	2.94
Dispensing	<u>1.27</u>	<u>1.00</u>	<u>1.07</u>
Total	7.62	8.39	9.14

Source: SFA Pacific, Inc.

5.1.2.3. Challenges

Multiple challenges must be overcome to achieve the vision of secure, abundant, inexpensive, and clean hydrogen production with low carbon emissions.

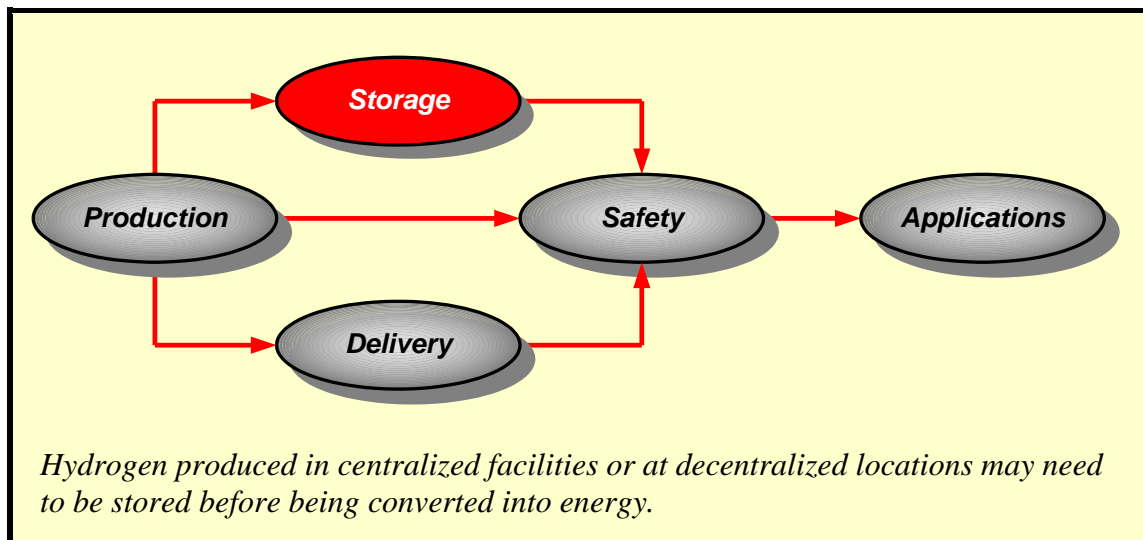
The hydrogen production costs are high relative to conventional fuels. With most hydrogen currently produced from hydrocarbons, the cost per unit of energy delivered through hydrogen is higher than the cost of the same unit of energy from the hydrocarbon itself. This is especially the case when the comparison is made at the point of sale to the customer, as delivery cost for hydrogen is also higher than for hydrocarbons. The large-scale, well-developed production and delivery infrastructures for natural gas, oil, coal, and electricity keep energy process low and set a tough price point for hydrogen to meet.

The low demand for hydrogen inhibits development of production capacity. Although there is a healthy, growing market for hydrogen in refineries and chemical plants, there is little demand for hydrogen as an energy carrier. Demand growth will depend on the development and implementation of hydrogen storage and

conversion devices, and on a demand pull from products such as hydrogen-powered cars and electric generators. Without demand for high-quality hydrogen in the merchant energy carrier market, there is little incentive for industry to completely develop, optimize, and implement existing and new technologies.

Current technologies produce large quantities of carbon dioxide and are not optimized for making hydrogen as an energy carrier. Existing production technologies can produce vast amounts of hydrogen from hydrocarbon but emit large amount of carbon dioxide into the atmosphere. Existing commercial production methods (such as steam methane reformation, multi-fuel gasification, and electrolysis) require technical improvements to reduce costs, improve efficiencies, and produce inexpensive, high-purity hydrogen with little or no carbon emissions.

5.1.3. Storage



Storage issues cut across the production, transport, delivery, and end-use applications of hydrogen as an energy carrier. Mobile applications are driving the development of safe, space-efficient, and cost-effective hydrogen storage systems. Use of hydrogen as an energy carrier requires that it be stored and transmitted. The primary methods for hydrogen storage are compressed gas, liquefied hydrogen, metal hydride, and carbon-based systems. Most of these systems may be used either for stationary applications or for onboard vehicle storage. Long term (~100 days), seasonal storage of hydrogen is generally in the form of chemical hydrides.

Hydrogen can be stored as a discrete gas or liquid or in a chemical compound. Currently available technologies permit the physical storage, transport, and delivery of gaseous or liquid hydrogen in tanks and pipeline systems. The storage of compressed hydrogen in tanks is the most mature technology, though the very low density of hydrogen translates to inefficient use of space onboard a vehicle. This

inefficiency can be mitigated with higher compression, such as 5,000 to 10,000 psi. Storage tank designs are advancing with increased strength-to-weight ratio materials and optimized structures that provide better containment, reduced weight and volume, improved impact resistance, and improved safety.

Liquid hydrogen takes up less storage volume than gas but requires cryogenic containers. A major concern in liquid hydrogen storage is minimizing losses from liquid boil-off. Any evaporation will result in a net loss in system efficiency, because work went into liquefying the hydrogen, but there will be an even greater loss of the hydrogen is released into the atmosphere instead of being recovered.

Even with careful insulation, some hydrogen will evaporate. This hydrogen can be vented, allowed to build up pressure in the storage vessel, or captured and returned to the liquefaction process. If the hydrogen cannot be recovered, venting the hydrogen to the atmosphere poses little safety risk because it will quickly diffuse into the air.

On-site storage allows continuous hydrogen plant operation in order to achieve higher utilization rates. It is more practical to store large amounts of hydrogen as a liquid. At less than \$5/gallon (physical volume) capital cost, liquid hydrogen storage is relatively inexpensive compared to compressed gaseous hydrogen. The following table shows that hydrogen is the lowest energy density fuel on earth.

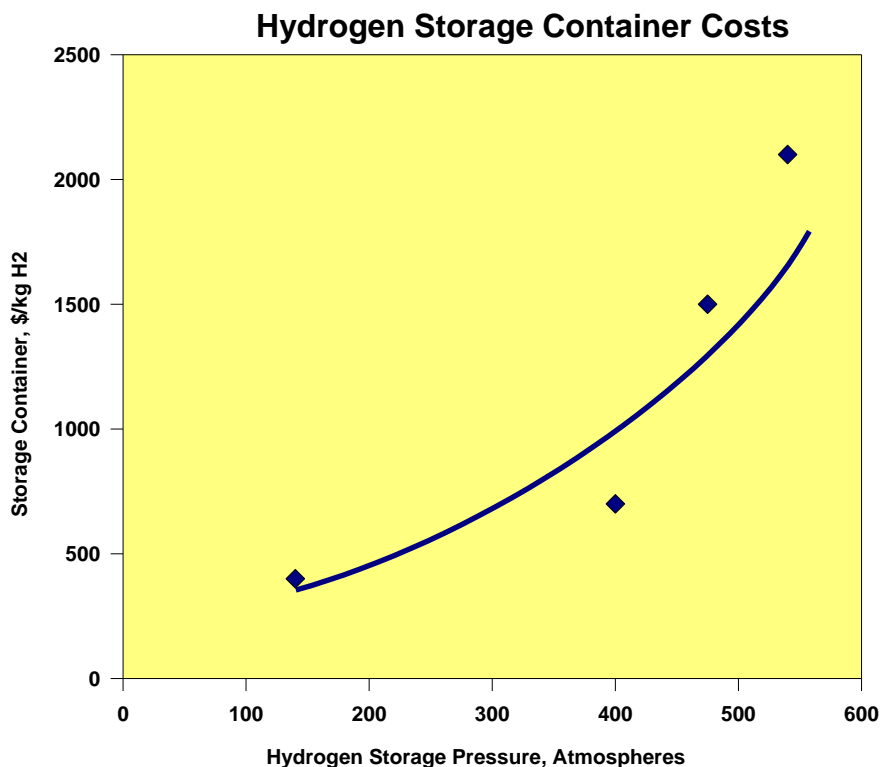
Density of Vehicle Fuel

Fuel Type	Density (kg/l)
Compressed Hydrogen	0.016
Gasoline	0.8
Methanol	0.72

It would take 3.73 gallons of liquid hydrogen to provide equivalent energy of one gallon of gasoline.

Gaseous hydrogen has to be pressurized for storage. At the base pressure of 6,000 PSIG, it would require about 8 gallons of gaseous hydrogen to have the same energy content as one gallon of gasoline. The higher the gas pressure, the lower the storage volume needed. However, the tube becomes weight limited as the thickness of the steel well increases to prevent embrittlement (cracking caused by hydrogen migrating into the metal).

The chart below shows how the cost of gaseous storage tubes increases with pressure. The cost could increase from less than \$400/kg hydrogen at 140 atmospheres to \$2,100/kg at 540 atmospheres.



Source: SFA Pacific, Inc.

Hydrogen can be stored at high densities as reversible metal hydrides or absorbed on carbon structures. When the hydrogen is needed, it can be released from these materials under certain temperature and pressure conditions. Hydrides are unique because some can adsorb hydrogen at or below atmospheric pressure, then release the hydrogen at significantly higher pressures when heated.

Complex-based reversible hydrides such as alanates have recently demonstrated improved weight performance over metal hydrides along with modest temperatures for hydrogen recovery. The most promising carbon materials for hydrogen storage at this time appear to be carbon nanotubes.

Chemical hydrides are emerging as another alternate to direct storage. The chemical hydrides considered for storage applications are a class of compounds that can be stored in solution as an alkaline liquid. Since the hydrogen is chemically bound in the compound and released by a catalyzed process, chemical hydrides present an inherently safer option than the storage of volatile and flammable fuel, be it hydrogen, gasoline, methanol, etc.

No current technology appears to satisfy all of the desired storage criteria sought by manufacturers and end users. Compressed hydrogen storage is a mature technology, though improvements in cost, weight, and volume storage efficiency must continue to be made. Several automotive manufacturers are considering liquid

hydrogen storage because of its good volumetric storage efficiency; however the special handling requirements, long-term storage losses, cryogenic liquefaction energy demands currently detract from its commercial viability. Metal hydrides offer the advantages of lower pressure storage, conformable shapes, and reasonable volumetric storage efficiency, but have weight penalties and thermal management issues. Although chemical hydrides present a potentially safer and more volumetrically efficient option, there are a number of challenges that must be addressed, including cost, recycling, overall energy efficiency, and infrastructure. Adsorbing materials with high surface areas are emerging, but the design of practical systems awaits a better understanding of the fundamental adsorption/desorption processes and development of high-volume manufacturing processes for the materials.

Hydrogen Storage Alternatives

Compressed Fuel Storage	<ul style="list-style-type: none"> • Cylindrical tanks • Quasi-conformable tanks
Liquid Hydrogen Storage	<ul style="list-style-type: none"> • Cylindrical tanks • Elliptical tanks • Cryotanks • HP liquid tanks
Solid State Conformable Storage	<ul style="list-style-type: none"> • Hydride materials
Chemical Hydrides	<ul style="list-style-type: none"> • Carbon adsorption • Off-board recycling

5.1.3.1. Application

If hydrogen is required for a cryogenic application, the only choice is liquid hydrogen. If on the other hand, hydrogen can be used as a gas, this would allow for all forms of storage and delivery systems to be considered.

5.1.3.1.1. Energy Density

The energy density of the hydrogen may be an important consideration. For example, if the hydrogen must be delivered to a site far away, liquid hydrogen would probably be the best option.

Energy density can be expressed in terms of the volumetric energy or the weight density. This is important in the case of metal hydrides because that have a high volumetric density, but a low weight density. In other words, a metal hydride storage tank may take up little space, but it can weigh several tons. One of the reasons

metal hydrides are difficult to use in automobiles is weight limitation, but for stationary storage, size is usually of more concern than weight.

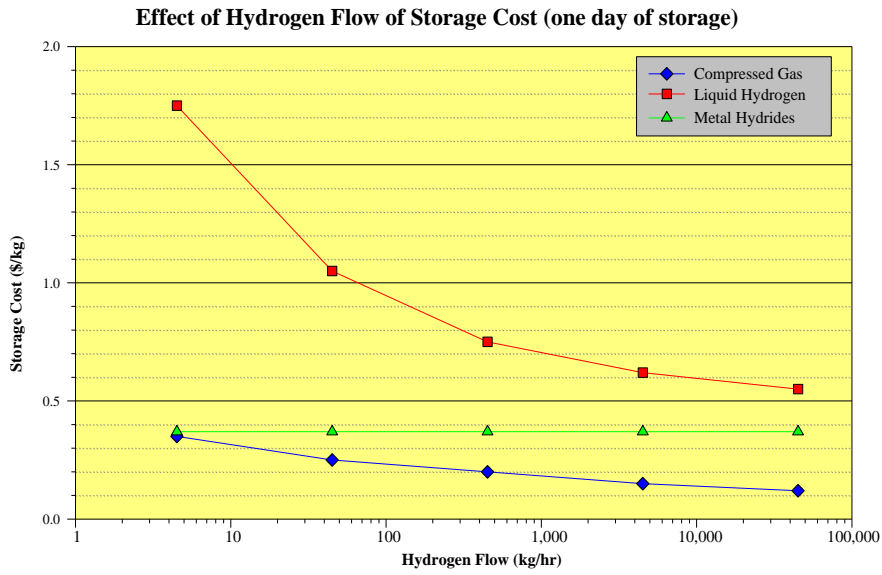
5.1.3.1.2. Quantity

The quantity of hydrogen to be stored is a major consideration because of the capital cost per kilogram is generally lower for larger capacity storage units. In the case of liquid hydrogen, boil-off rates are also inversely proportional to the vessel size; so larger storage units will have lower boil-off rates.

Compressed gas storage can be used for small quantities of hydrogen when cryogenic temperatures are not required. Because of the high capital cost of liquefaction plant, liquid hydrogen would be cost-prohibitive for small quantities of hydrogen, and the high boil-off rates associated with the smaller vessel size would raise this cost even more. A metal hydride might be a cost-effective option if the hydrogen is produced at a low pressure and a high pressure gas is required. A metal hydride could also be used if the hydrogen must be purified. With very small quantities of hydrogen the cost difference between compressed gas and metal hydride storage is not great because both require a pressure vessel and the metal hydride allow cost is small compared to the cost for small vessels.

For larger quantities of hydrogen, liquid hydrogen starts to become competitive because of the lower storage unit cost per kilogram of hydrogen. Compressed gas storage is generally limited to 1,300 kg of hydrogen because of the high capital costs. Over this, liquid hydrogen should be considered.

The following graph show the economy of scale drops the liquid hydrogen storage cost as the production rate increases.

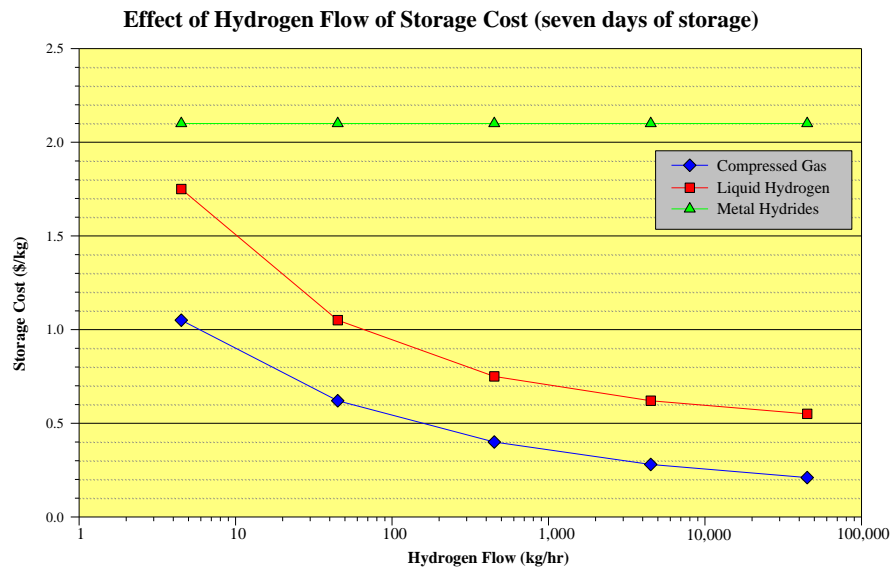
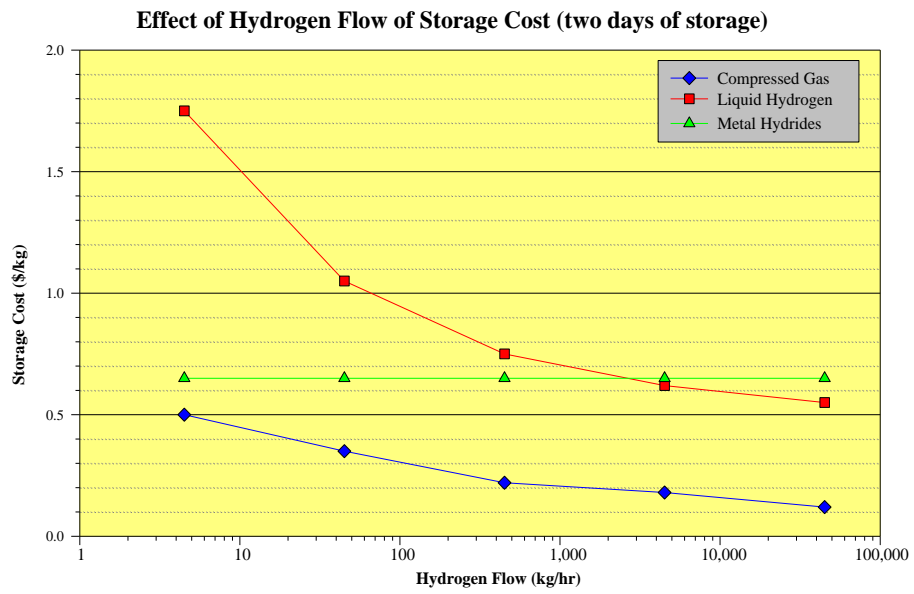


5.1.3.1.3. Storage Period

The longer hydrogen is to be stored, the more favorable liquid hydrogen storage becomes because of lower capital costs. If hydrogen is stored for a long time, the operating cost can be a small factor compared to the capital cost for storage.

Compressed gas storage should be considered for storage time of several hours to several days. Liquid storage should be considered for seasonal or long-term storage for periods longer than a couple of days. Metal hydride storage is not economical for large quantities of gas because of the high capital cost of the metal hydride.

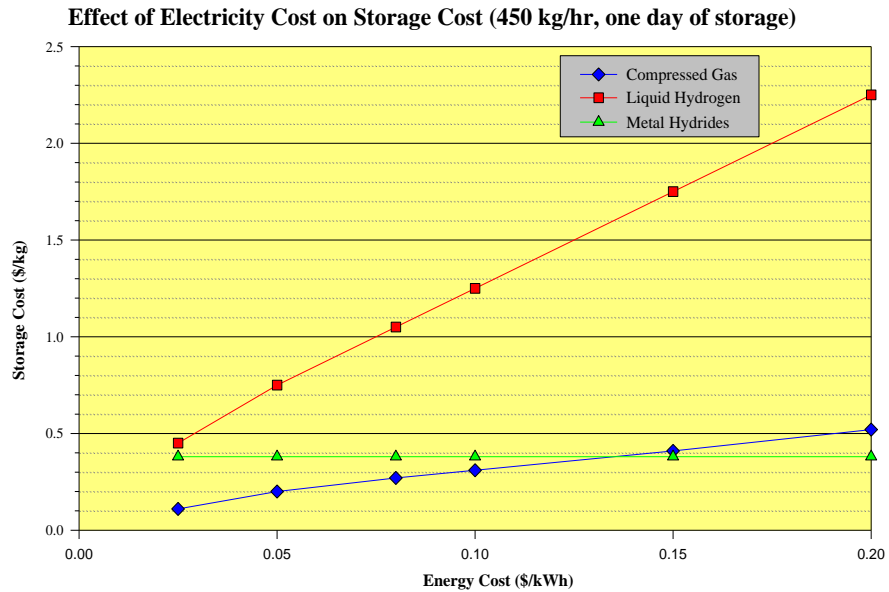
In addition to the graph above, the following graphs show how increasing the storage time makes the liquid storage more competitive and the metal hydrides less competitive.



5.1.3.1.4. Energy Availability

The available energy may be another consideration when choosing methods for storage. For compressed gas storage and hydrogen liquefaction, compressor power consumption can be quite high. In inexpensive electricity, gas turbine, or steam turbine power is available, the compression costs will be lower. A source of thermal energy of waste heat would benefit metal hydride storage by reducing the energy costs for releasing the hydrogen from the hydride.

The following chart shows the effect on electricity cost on the storage cost. This chart clearly shows that the electricity cost has the largest effect on liquid storage since it has the highest electricity requirement.



5.1.3.2. Challenges

Hydrogen storage must meet a number of challenges before hydrogen can become an acceptable energy option for the consumer. The technology must be made transparent to the end user – similar to today's experience with gasoline-powered vehicles.

Hydrogen storage is a critical element in the hydrogen cycle, from production and delivery to energy conversion and applications. New media development is needed to provide reversible, low-temperature, high-density storage of hydrogen. These storage characteristics generally describe the technical goals for some solid-state materials, including hydrides and carbon adsorption materials. The ultimate hydrogen storage system for meeting manufacturer, consumer, and end-user expectations would be low cost and energy efficient, and offer inherent safety.

Energy storage densities are insufficient to gain market acceptance. This barrier directly relates to making hydrogen storage transparent to the consumer and end-user. Specifically, transparency would mean a hydrogen storage system that enables a vehicle to travel 300 to 400 miles and fits in an envelope that does not compromise either passenger or storage space. Fundamental limitations on hydrogen density will ultimately limit storage performance. The performance of vehicles, therefore, depends on the overall system performance – the combined vehicle efficiency, energy conversion efficiency, and storage efficiency.

As there are few hydrogen-fueled vehicles on the road today, the more mature compressed and liquid storage technologies are quite expensive. High-pressure cylinders will be produced with high-volume production, once there is sufficient demand. Raw material cost could also be reduced substantially if there were a high enough demand. The initially low rates at which automakers expect to introduce fuel cell vehicles will present a challenge to the commercialization and cost reduction of hydrogen storage technologies.

What Consumers Want

With transparency as acknowledged target, it is important to understand consumers' expectations for fuel storage on a vehicle. Simply put, consumers do not think about fuel storage. They do not see the fuel tank. They expect maximum passenger and trunk space. They expect 300 to 400 miles range on "a tank of gas" before having to fill-up. They expect to fill up their "tank" in less than 3-5 minutes. They are used to self-serve "gas stations" that are virtually foolproof, with a simple trigger-type nozzle that starts with a push of a button or flick of a lever. They expect to be able to refuel at the corner gas station, although refueling at home would be preferred. Probably the only time most consumers think about fuel, let alone fuel storage, is when fuel prices rise to \$2.00 per gallon of gasoline.

5.1.3.3. *Conclusions*

The lack of low-cost and lightweight storage devices as well as commercially available and cost-competitive fuel cells interferes with the implementation of hydrogen as an energy carrier. One of the keys for a “hydrogen economy” to evolve is that consumers will need to have convenient access to hydrogen and storage devices. Better hydrogen storage systems will offer easy access to hydrogen for vehicles, distributed energy facilities, or central station power plants.

The most challenging application is the automobile. Automobiles impose the greatest constraints with respect to available space on-board the vehicle and the greatest consumer expectations for energy density or vehicle range. In the near-term, fuel cell vehicles are likely to be introduced first in fleet applications. Since fleet applications typically have centralized refueling facilities, a vehicle range of 100 to 150 miles would be acceptable. In terms of mass of hydrogen, this range could be achieved with about 3 kilograms of hydrogen supplying a fuel cell vehicle. Mature compressed and liquid hydrogen storage technologies of reasonable size and weight could achieve this short-term goal.

In the longer term, average consumers will expect fuel cell vehicles to provide the same cost, convenience, and operational characteristics as gasoline-powered vehicles. In fact, it is likely that fuel cell vehicles will have to offer a significant value to encourage consumers to adopt a new technology. Vehicle range will be an important factor to consumers, especially as a hydrogen-refueling infrastructure begins to develop. Fuel cell ranges of 300 to 400 miles will be needed, requiring roughly 5 kilograms of hydrogen to be stored on-board. Advanced storage methods, including advancements in compressed storage, cryogas tanks, and carbon nanostructures, will have to be made to reduce hydrogen storage system size, weight, and cost without sacrificing safety or consumer convenience.

Hydrogen Storage Assumptions		
Compressor Capital Cost	\$1,000	per kW
Comp. Gas Capital Cost	\$1,323	per kg
Liquefaction Capital Cost	\$44,093	per kg/hr
Liquid Dewar Capital Cost	\$441	per kg
Hydride Capital Cost	\$2,205	per kg
Compressor Size	4,000	kW
Comp. Gas Tank Size	227	kg
Liquefaction Size	454	kg/hr
Liquid Dewar Size	45	kg
Compressor Pressure	20	MPa
Comp. Pressure Scale Up	0.18	
Comp. Gas Tank Pressure	20	MPa
Tank Pressure Scale Up	0.44	
Comp. Cost Scale Up	0.80	
Comp. Gas Tank Scale Up	0.75	
Liquefaction Scale Up	0.65	
Dewar Scale Up	0.70	
Hydride Scale Up	1.00	
Compressor Power	2.2	kW/kg (20 MPa)
Compressor Cooling	50	liter/kg (20 MPa)
Liquefaction Power	9.9	KW/kg
Liquefaction Cooling	626	liter/kg
Boil-Off Rate	0.1	% per day
Hydride Cooling	209	liter/kg
Hydride Heating	23,260	kJ/kg
Electric Cost	\$0.05	per kW
Steam Cost	\$3.79	per GJ
Cooling Cost	\$0.02	per M liters
Operating Days/Year	350	days/years
Depreciation	22	years

COMPRESSED GAS STORAGE - SI Units

Compressor Capital Cost= \$1,000 per kW
 Comp. Gas Capital Cost= \$1,323 per kg
 Compressor Size= 4,000 kW
 Comp. Gas Tank Size= 227 kg
 Compressor Pressure= 20 MPa
 Comp. Pressure Scale-Up= 0.18
 Comp. Gas Tank Pressure= 20 MPa
 Tank Pressure Scale-Up= 0.44
 Comp. Cost Scale-Up= 0.80
 Comp. Gas Tank Scale-Up= 0.75
 Compressor Power= 2.20 kWh/kg (20 MPa)
 Compressor Cooling= 50 gal/kg (20 MPa)
 Electric Cost= \$0.05 per kWh
 Cooling Cost= \$0.02 per M liters
 Operating Days/Year= 350 days/yr
 Depreciation= 22 years

Production Rate (kg/hr)	Days of Storage (days)	Operating Pressure (MPa)	Storage Capacity (kg)	Annual Production (kg/yr)	Compressor Power (kW/hr)	Cooling Water (liter/hr)	Compressor Size (kW)	Compressor Cost (\$)	Tank Cost (\$)	Total Capital Cost (\$)
5	1	20	109	38,102	10	227	10	\$33,145	\$173,002	\$206,147
45	1	20	1,089	381,016	100	2,271	100	\$209,128	\$972,864	\$1,181,992
454	1	20	10,886	3,810,156	1,000	22,712	1,000	\$1,319,508	\$5,470,817	\$6,790,325
4,536	1	20	108,862	38,101,560	10,000	227,124	10,000	\$8,325,532	\$30,764,664	\$39,090,197
45,359	1	20	1,088,616	381,015,600	100,000	2,271,240	100,000	\$52,530,556	\$173,002,422	\$225,532,978
5	2	20	218	38,102	10	227	10	\$33,145	\$290,954	\$324,099
45	2	20	2,177	381,016	100	2,271	100	\$209,128	\$1,636,156	\$1,845,284
454	2	20	21,772	3,810,156	1,000	22,712	1,000	\$1,319,508	\$9,200,781	\$10,520,289
4,536	2	20	217,723	38,101,560	10,000	227,124	10,000	\$8,325,532	\$51,739,792	\$60,065,324
45,359	2	20	2,177,232	381,015,600	100,000	2,271,240	100,000	\$52,530,556	\$290,954,233	\$343,484,789
5	4	20	435	38,102	10	227	10	\$33,145	\$489,325	\$522,469
45	4	20	4,354	381,016	100	2,271	100	\$209,128	\$2,751,675	\$2,960,803
454	4	20	43,545	3,810,156	1,000	22,712	1,000	\$1,319,508	\$15,473,807	\$16,793,315
4,536	4	20	435,446	38,101,560	10,000	227,124	10,000	\$8,325,532	\$87,015,611	\$95,341,144
45,359	4	20	4,354,464	381,015,600	100,000	2,271,240	100,000	\$52,530,556	\$489,324,743	\$541,855,299
5	7	20	762	38,102	10	227	10	\$33,145	\$744,519	\$777,663
45	7	20	7,620	381,016	100	2,271	100	\$209,128	\$4,186,737	\$4,395,865
454	7	20	76,203	3,810,156	1,000	22,712	1,000	\$1,319,508	\$23,543,754	\$24,863,262
4,536	7	20	762,031	38,101,560	10,000	227,124	10,000	\$8,325,532	\$132,396,259	\$140,721,791
45,359	7	20	7,620,312	381,015,600	100,000	2,271,240	100,000	\$52,530,556	\$744,518,876	\$797,049,432
5	14	20	1,524	38,102	10	227	10	\$33,145	\$1,252,127	\$1,285,271
45	14	20	15,241	381,016	100	2,271	100	\$209,128	\$7,041,225	\$7,250,353
454	14	20	152,406	3,810,156	1,000	22,712	1,000	\$1,319,508	\$39,595,717	\$40,915,225
4,536	14	20	1,524,062	38,101,560	10,000	227,124	10,000	\$8,325,532	\$222,663,079	\$230,988,611
45,359	14	20	15,240,624	381,015,600	100,000	2,271,240	100,000	\$52,530,556	\$1,252,126,507	\$1,304,657,063
5	30	20	3,266	38,102	10	227	10	\$33,145	\$2,217,651	\$2,250,795
45	30	20	32,658	381,016	100	2,271	100	\$209,128	\$12,470,766	\$12,679,894
454	30	20	326,585	3,810,156	1,000	22,712	1,000	\$1,319,508	\$70,128,270	\$71,447,778
4,536	30	20	3,265,848	38,101,560	10,000	227,124	10,000	\$8,325,532	\$394,360,241	\$402,685,773
45,359	30	20	32,658,480	381,015,600	100,000	2,271,240	100,000	\$52,530,556	\$2,217,650,608	\$2,270,181,164

Production Rate (kg/hr)	Days of Storage (days)	Depreciation (\$/yr)	Annual Electricity Cost (\$/yr)	Annual Cooling Water Cost (\$/yr)	Total Annual Cost (\$/yr)	Capital Cost (\$/kg)	Energy Cost (\$/kg)	Cooling Cost (\$/kg)	Total Cost (\$/kg)	Comp. Cost (\$/kg)	Tank Cost (\$/kg)	Comp. Capital (\$/kW)	Tank Capital (\$/kg)
5	1	\$9,370	\$4,200	\$35	\$13,606	\$0.25	\$0.11	\$0.00	\$0.36	\$0.04	\$0.21	\$3,314	\$1,589
45	1	\$53,727	\$42,000	\$353	\$96,080	\$0.14	\$0.11	\$0.00	\$0.25	\$0.02	\$0.12	\$2,091	\$894
454	1	\$308,651	\$420,000	\$3,528	\$732,179	\$0.08	\$0.11	\$0.00	\$0.19	\$0.02	\$0.07	\$1,320	\$503
4,536	1	\$1,776,827	\$4,200,000	\$35,280	\$6,012,107	\$0.05	\$0.11	\$0.00	\$0.16	\$0.01	\$0.04	\$833	\$283
45,359	1	\$10,251,499	\$42,000,000	\$352,800	\$52,604,299	\$0.03	\$0.11	\$0.00	\$0.14	\$0.01	\$0.02	\$525	\$159
5	2	\$14,732	\$4,200	\$35	\$18,967	\$0.39	\$0.11	\$0.00	\$0.50	\$0.04	\$0.35	\$3,314	\$1,336
45	2	\$83,877	\$42,000	\$353	\$126,229	\$0.22	\$0.11	\$0.00	\$0.33	\$0.02	\$0.20	\$2,091	\$751
454	2	\$478,195	\$420,000	\$3,528	\$901,723	\$0.13	\$0.11	\$0.00	\$0.24	\$0.02	\$0.11	\$1,320	\$423
4,536	2	\$2,730,242	\$4,200,000	\$35,280	\$6,965,522	\$0.07	\$0.11	\$0.00	\$0.18	\$0.01	\$0.06	\$833	\$238
45,359	2	\$15,612,945	\$42,000,000	\$352,800	\$57,965,745	\$0.04	\$0.11	\$0.00	\$0.15	\$0.01	\$0.03	\$525	\$134
5	4	\$23,749	\$4,200	\$35	\$27,984	\$0.62	\$0.11	\$0.00	\$0.73	\$0.04	\$0.58	\$3,314	\$1,124
45	4	\$134,582	\$42,000	\$353	\$176,935	\$0.35	\$0.11	\$0.00	\$0.46	\$0.02	\$0.33	\$2,091	\$632
454	4	\$763,332	\$420,000	\$3,528	\$1,186,860	\$0.20	\$0.11	\$0.00	\$0.31	\$0.02	\$0.18	\$1,320	\$355
4,536	4	\$4,333,688	\$4,200,000	\$35,280	\$8,568,968	\$0.11	\$0.11	\$0.00	\$0.22	\$0.01	\$0.10	\$833	\$200
45,359	4	\$24,629,786	\$42,000,000	\$352,800	\$66,982,586	\$0.06	\$0.11	\$0.00	\$0.18	\$0.01	\$0.06	\$525	\$112
5	7	\$35,348	\$4,200	\$35	\$39,584	\$0.93	\$0.11	\$0.00	\$1.04	\$0.04	\$0.89	\$3,314	\$977
45	7	\$199,812	\$42,000	\$353	\$242,165	\$0.52	\$0.11	\$0.00	\$0.64	\$0.02	\$0.50	\$2,091	\$549
454	7	\$1,130,148	\$420,000	\$3,528	\$1,553,676	\$0.30	\$0.11	\$0.00	\$0.41	\$0.02	\$0.28	\$1,320	\$309
4,536	7	\$6,396,445	\$4,200,000	\$35,280	\$10,631,725	\$0.17	\$0.11	\$0.00	\$0.28	\$0.01	\$0.16	\$833	\$174
45,359	7	\$36,229,520	\$42,000,000	\$352,800	\$78,582,320	\$0.10	\$0.11	\$0.00	\$0.21	\$0.01	\$0.09	\$525	\$98
5	14	\$58,421	\$4,200	\$35	\$62,657	\$1.53	\$0.11	\$0.00	\$1.64	\$0.04	\$1.49	\$3,314	\$822
45	14	\$329,561	\$42,000	\$353	\$371,914	\$0.86	\$0.11	\$0.00	\$0.98	\$0.02	\$0.84	\$2,091	\$462
454	14	\$1,859,783	\$420,000	\$3,528	\$2,283,311	\$0.49	\$0.11	\$0.00	\$0.60	\$0.02	\$0.47	\$1,320	\$260
4,536	14	\$10,499,482	\$4,200,000	\$35,280	\$14,734,762	\$0.28	\$0.11	\$0.00	\$0.39	\$0.01	\$0.27	\$833	\$146
45,359	14	\$59,302,594	\$42,000,000	\$352,800	\$101,655,394	\$0.16	\$0.11	\$0.00	\$0.27	\$0.01	\$0.15	\$525	\$82
5	30	\$102,309	\$4,200	\$35	\$106,544	\$2.69	\$0.11	\$0.00	\$2.80	\$0.04	\$2.65	\$3,314	\$679
45	30	\$576,359	\$42,000	\$353	\$618,712	\$1.51	\$0.11	\$0.00	\$1.62	\$0.02	\$1.49	\$2,091	\$382
454	30	\$3,247,626	\$420,000	\$3,528	\$3,671,154	\$0.85	\$0.11	\$0.00	\$0.96	\$0.02	\$0.84	\$1,320	\$215
4,536	30	\$18,303,899	\$4,200,000	\$35,280	\$22,539,179	\$0.48	\$0.11	\$0.00	\$0.59	\$0.01	\$0.47	\$833	\$121
45,359	30	\$103,190,053	\$42,000,000	\$352,800	\$145,542,853	\$0.27	\$0.11	\$0.00	\$0.38	\$0.01	\$0.26	\$525	\$68

Liquid Hydrogen Storage - SI Units

Liquefaction Capital Cost = \$44,093 per kg/hr
 Liquid Dewar Capital Cost = \$441 per kg/hr
 Liquefaction Size = 2,205 kg/hr
 Liquid Dewar Size = 220 kg/hr
 Liquefaction Scale-Up = 0.65
 Dewar Scale-Up = 0.7
 Liquefaction Power = 9.9 kWh/kg
 Liquefaction Cooling = 626 gal/lb
 Boil-off Rate = 0.10% per day
 Electric Cost = \$0.05 per kWh
 Cooling Cost = \$0.02 per M liters
 Operating Days/Year = 350 days/yr
 Depreciation = 22 years

Production Rate (kg/hr)	Days of Storage (days)	Production plus Boil-Off (kg/hr)	Storage Capacity (kg)	Annual Production (kg/yr)	Liquefier Power (kWh/hr)	Cooling Water (liters/hr)	Liquefier Cost (\$)	Dewar Cost (\$)	Total Capital Cost (\$)
5	1	5	109	38,102	45	2,842	\$1,003,026	\$36,939	\$1,039,964
45	1	45	1,090	381,016	450	28,419	\$4,480,351	\$185,132	\$4,665,483
454	1	454	10,897	3,810,156	4,504	284,189	\$20,012,991	\$927,858	\$20,940,849
4,536	1	4,540	108,970	38,101,560	45,045	2,841,888	\$89,394,748	\$4,650,306	\$94,045,055
45,359	1	45,404	1,089,704	381,015,600	450,450	28,418,876	\$399,311,672	\$23,306,742	\$422,618,414
5	2	5	218	38,102	45	2,845	\$1,003,676	\$60,049	\$1,063,725
45	2	45	2,182	381,016	451	28,447	\$4,483,255	\$300,958	\$4,784,213
454	2	454	21,816	3,810,156	4,509	284,472	\$20,025,965	\$1,508,362	\$21,534,327
4,536	2	4,545	218,158	38,101,560	45,090	2,844,722	\$89,452,700	\$7,559,719	\$97,012,419
45,359	2	45,450	2,181,582	381,015,600	450,899	28,447,224	\$399,570,532	\$37,888,347	\$437,458,879
5	4	5	437	38,102	45	2,850	\$1,004,974	\$97,686	\$1,102,659
45	4	46	4,372	381,016	452	28,504	\$4,489,052	\$489,588	\$4,978,641
454	4	455	43,718	3,810,156	4,518	285,038	\$20,051,860	\$2,453,754	\$22,505,614
4,536	4	4,554	437,185	38,101,560	45,180	2,850,384	\$89,568,368	\$12,297,902	\$101,866,271
45,359	4	45,540	4,371,847	381,015,600	451,796	28,503,835	\$400,087,205	\$61,635,516	\$461,722,721
5	7	5	767	38,102	45	2,859	\$1,006,914	\$144,830	\$1,151,744
45	7	46	7,673	381,016	453	28,589	\$4,497,719	\$725,871	\$5,223,590
454	7	457	76,735	3,810,156	4,531	285,885	\$20,090,572	\$3,637,975	\$23,728,547
4,536	7	4,568	767,347	38,101,560	45,314	2,858,854	\$89,741,288	\$18,233,068	\$107,974,356
45,359	7	45,675	7,673,468	381,015,600	453,139	28,588,540	\$400,859,610	\$91,381,807	\$492,241,417
5	14	5	1,545	38,102	46	2,879	\$1,011,411	\$236,409	\$1,247,820
45	14	46	15,453	381,016	456	28,785	\$4,517,805	\$1,184,854	\$5,702,659
454	14	460	154,525	3,810,156	4,563	287,852	\$20,180,295	\$5,938,337	\$26,118,632
4,536	14	4,599	1,545,251	38,101,560	45,626	2,878,520	\$90,142,066	\$29,762,185	\$119,904,251
45,359	14	45,990	15,452,506	381,015,600	456,256	28,785,198	\$402,649,820	\$149,164,272	\$551,814,092
5	30	5	3,362	38,102	46	2,923	\$1,021,532	\$407,396	\$1,428,929
45	30	47	33,624	381,016	463	29,230	\$4,563,017	\$2,041,819	\$6,604,836
454	30	467	336,237	3,810,156	4,633	292,296	\$20,382,247	\$10,233,337	\$30,615,584
4,536	30	4,670	3,362,368	38,101,560	46,330	2,922,957	\$91,044,153	\$51,288,178	\$142,332,331
45,359	30	46,700	33,623,684	381,015,600	463,300	29,229,566	\$406,679,291	\$257,049,801	\$663,729,093

Production Rate (kg/hr)	Days of Storage (days)	Depreciation (\$/yr)	Annual Electricity Cost (\$/yr)	Annual Cooling Water Cost (\$/yr)	Total Annual Cost (\$/yr)	Capital Cost (\$/kg)	Energy Cost (\$/kg)	Cooling Cost (\$/kg)	Total Cost (\$/kg)	Liquefier Cost (\$/kg)	Dewar Cost (\$/kg)	Liquefier Capital (\$/kW)	Dewar Capital (\$/kg)
5	1	\$47,271	\$18,919	\$441	\$66,631	\$1.24	\$0.50	\$0.01	\$1.75	\$1.20	\$0.04	\$221,130	\$339
45	1	\$212,067	\$189,189	\$4,414	\$405,671	\$0.56	\$0.50	\$0.01	\$1.06	\$0.53	\$0.02	\$98,775	\$170
454	1	\$951,857	\$1,891,889	\$44,144	\$2,887,890	\$0.25	\$0.50	\$0.01	\$0.76	\$0.24	\$0.01	\$44,121	\$85
4,536	1	\$4,274,775	\$18,918,891	\$441,441	\$23,635,107	\$0.11	\$0.50	\$0.01	\$0.62	\$0.11	\$0.01	\$19,708	\$43
45,359	1	\$19,209,928	\$189,188,906	\$4,414,408	\$212,813,241	\$0.05	\$0.50	\$0.01	\$0.56	\$0.05	\$0.00	\$8,803	\$21
5	2	\$48,351	\$18,938	\$442	\$67,731	\$1.27	\$0.50	\$0.01	\$1.78	\$0.20	\$0.07	\$221,274	\$275
45	2	\$217,464	\$189,378	\$4,419	\$411,261	\$0.57	\$0.50	\$0.01	\$1.08	\$0.53	\$0.04	\$98,839	\$138
454	2	\$978,833	\$1,893,776	\$44,188	\$2,916,797	\$0.26	\$0.50	\$0.01	\$0.77	\$0.24	\$0.02	\$44,150	\$69
4,536	2	\$4,409,655	\$18,937,762	\$441,881	\$23,789,299	\$0.12	\$0.50	\$0.01	\$0.62	\$0.11	\$0.01	\$19,721	\$35
45,359	2	\$19,884,494	\$189,377,622	\$4,418,811	\$213,680,928	\$0.05	\$0.50	\$0.01	\$0.56	\$0.05	\$0.00	\$8,809	\$17
5	4	\$50,121	\$18,975	\$443	\$69,539	\$1.32	\$0.50	\$0.01	\$1.83	\$0.20	\$0.12	\$221,560	\$223
45	4	\$226,302	\$189,754	\$4,428	\$420,484	\$0.59	\$0.50	\$0.01	\$1.10	\$0.54	\$0.06	\$98,967	\$112
454	4	\$1,022,982	\$1,897,545	\$44,276	\$2,964,803	\$0.27	\$0.50	\$0.01	\$0.78	\$0.24	\$0.03	\$44,207	\$56
4,536	4	\$4,630,285	\$18,975,449	\$442,760	\$24,048,495	\$0.12	\$0.50	\$0.01	\$0.63	\$0.11	\$0.01	\$19,747	\$28
45,359	4	\$20,987,396	\$189,754,490	\$4,427,605	\$215,169,491	\$0.06	\$0.50	\$0.01	\$0.56	\$0.05	\$0.01	\$8,820	\$14
5	7	\$52,352	\$19,032	\$444	\$71,828	\$1.37	\$0.50	\$0.01	\$1.89	\$0.20	\$0.17	\$221,988	\$189
45	7	\$237,436	\$190,318	\$4,441	\$432,195	\$0.62	\$0.50	\$0.01	\$1.13	\$0.54	\$0.09	\$99,158	\$95
454	7	\$1,078,570	\$1,903,184	\$44,408	\$3,026,162	\$0.28	\$0.50	\$0.01	\$0.79	\$0.24	\$0.04	\$44,292	\$47
4,536	7	\$4,907,925	\$19,031,838	\$444,076	\$24,383,840	\$0.13	\$0.50	\$0.01	\$0.64	\$0.11	\$0.02	\$19,785	\$24
45,359	7	\$22,374,610	\$190,318,380	\$4,440,762	\$217,133,752	\$0.06	\$0.50	\$0.01	\$0.57	\$0.05	\$0.01	\$8,837	\$12
5	14	\$56,719	\$19,163	\$447	\$76,329	\$1.49	\$0.50	\$0.01	\$2.00	\$0.21	\$0.28	\$222,979	\$153
45	14	\$259,212	\$191,628	\$4,471	\$455,311	\$0.68	\$0.50	\$0.01	\$1.19	\$0.54	\$0.14	\$99,601	\$77
454	14	\$1,187,211	\$1,916,276	\$44,713	\$3,148,199	\$0.31	\$0.50	\$0.01	\$0.83	\$0.24	\$0.07	\$44,490	\$38
4,536	14	\$5,450,193	\$19,162,756	\$447,131	\$25,060,081	\$0.14	\$0.50	\$0.01	\$0.66	\$0.11	\$0.04	\$19,873	\$19
45,359	14	\$25,082,459	\$191,627,564	\$4,471,310	\$221,181,333	\$0.07	\$0.50	\$0.01	\$0.58	\$0.05	\$0.02	\$8,877	\$10
5	30	\$64,951	\$19,459	\$454	\$84,864	\$1.70	\$0.51	\$0.01	\$2.23	\$0.22	\$0.49	\$225,210	\$121
45	30	\$300,220	\$194,586	\$4,540	\$499,346	\$0.79	\$0.51	\$0.01	\$1.31	\$0.54	\$0.24	\$100,598	\$61
454	30	\$1,391,617	\$1,945,858	\$45,403	\$3,382,879	\$0.37	\$0.51	\$0.01	\$0.89	\$0.24	\$0.12	\$44,935	\$30
4,536	30	\$6,469,651	\$19,458,579	\$454,034	\$26,382,264	\$0.17	\$0.51	\$0.01	\$0.69	\$0.11	\$0.06	\$20,072	\$15
45,359	30	\$30,169,504	\$194,585,794	\$4,540,335	\$229,295,634	\$0.08	\$0.51	\$0.01	\$0.60	\$0.05	\$0.03	\$8,966	\$8

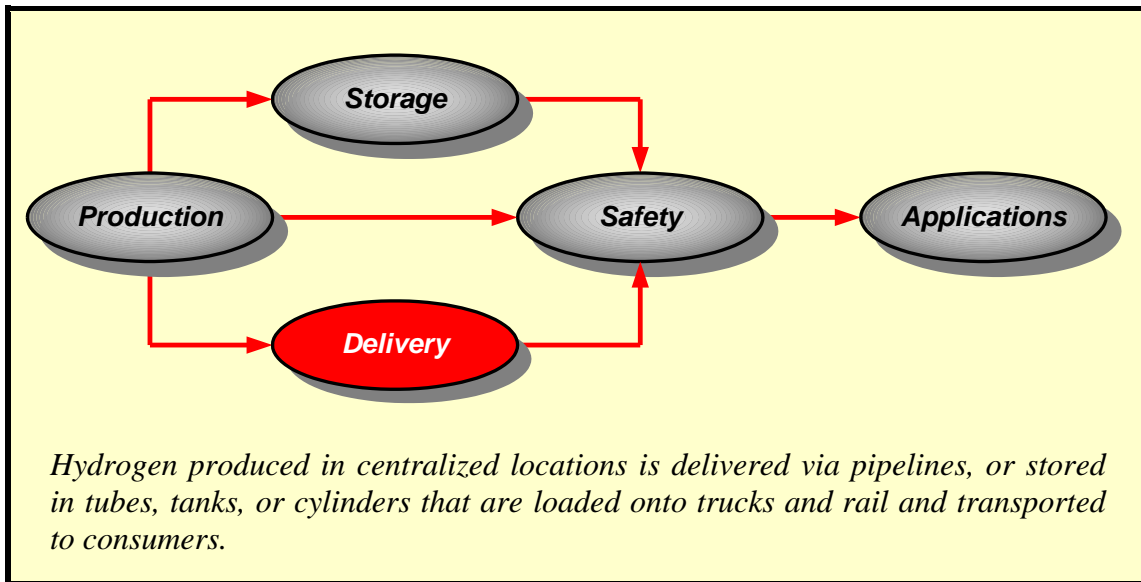
Metal Hydride Storage - SI Units

Hydride Capital Cost = \$2,205 per kg
 Hydride Scale-Up = 1 per kg/hr
 Hydride Cooling = 209 liters/kg
 Hydride Heating = 23,260 kJ/kg
 Steam Cost = \$4 per kJ
 Cooling Cost = \$0 per M liters
 Operating Days/Year = 350 days/yr
 Depreciation = 22 years

Production Rate (kg/hr)	Days of Storage (days)	Storage Capacity (kg)	Annual Production (kg/yr)	Heat Requirement (kJ/hr)	Cooling Requirement (liters/hr)	Hydride Cost (\$)	Total Capital Cost (\$)
5	1	\$109	\$38,102	\$105,506	\$946	\$240,000.00	\$240,000.00
45	1	\$1,089	\$381,016	\$1,055,060	\$9,464	\$2,400,000.00	\$2,400,000.00
454	1	\$10,886	\$3,810,156	\$10,550,600	\$94,635	\$24,000,000.00	\$24,000,000.00
4,536	1	\$108,862	\$38,101,560	\$105,506,000	\$946,350	\$240,000,000.00	\$240,000,000.00
45,359	1	\$1,088,616	\$381,015,600	\$1,055,060,000	\$9,463,500	\$2,400,000,000.00	\$2,400,000,000.00
5	2	\$218	\$38,102	\$105,506	\$946	\$480,000.00	\$480,000.00
45	2	\$2,177	\$381,016	\$1,055,060	\$9,464	\$4,800,000.00	\$4,800,000.00
454	2	\$21,772	\$3,810,156	\$10,550,600	\$94,635	\$48,000,000.00	\$48,000,000.00
4,536	2	\$217,723	\$38,101,560	\$105,506,000	\$946,350	\$480,000,000.00	\$480,000,000.00
45,359	2	\$2,177,232	\$381,015,600	\$1,055,060,000	\$9,463,500	\$4,800,000,000.00	\$4,800,000,000.00
5	4	\$435	\$38,102	\$105,506	\$946	\$960,000.00	\$960,000.00
45	4	\$4,354	\$381,016	\$1,055,060	\$9,464	\$9,600,000.00	\$9,600,000.00
454	4	\$43,545	\$3,810,156	\$10,550,600	\$94,635	\$96,000,000.00	\$96,000,000.00
4,536	4	\$435,446	\$38,101,560	\$105,506,000	\$946,350	\$960,000,000.00	\$960,000,000.00
45,359	4	\$4,354,464	\$381,015,600	\$1,055,060,000	\$9,463,500	\$9,600,000,000.00	\$9,600,000,000.00
5	7	\$762	\$38,102	\$105,506	\$946	\$1,680,000.00	\$1,680,000.00
45	7	\$7,620	\$381,016	\$1,055,060	\$9,464	\$16,800,000.00	\$16,800,000.00
454	7	\$76,203	\$3,810,156	\$10,550,600	\$94,635	\$168,000,000.00	\$168,000,000.00
4,536	7	\$762,031	\$38,101,560	\$105,506,000	\$946,350	\$1,680,000,000.00	\$1,680,000,000.00
45,359	7	\$7,620,312	\$381,015,600	\$1,055,060,000	\$9,463,500	\$16,800,000,000.00	\$16,800,000,000.00
5	14	\$1,524	\$38,102	\$105,506	\$946	\$3,360,000.00	\$3,360,000.00
45	14	\$15,241	\$381,016	\$1,055,060	\$9,464	\$33,600,000.00	\$33,600,000.00
454	14	\$152,406	\$3,810,156	\$10,550,600	\$94,635	\$336,000,000.00	\$336,000,000.00
4,536	14	\$1,524,062	\$38,101,560	\$105,506,000	\$946,350	\$3,360,000,000.00	\$3,360,000,000.00
45,359	14	\$15,240,624	\$381,015,600	\$1,055,060,000	\$9,463,500	\$33,600,000,000.00	\$33,600,000,000.00
5	30	\$3,266	\$38,102	\$105,506	\$946	\$7,200,000.00	\$7,200,000.00
45	30	\$32,658	\$381,016	\$1,055,060	\$9,464	\$72,000,000.00	\$72,000,000.00
454	30	\$326,585	\$3,810,156	\$10,550,600	\$94,635	\$720,000,000.00	\$720,000,000.00
4,536	30	\$3,265,848	\$38,101,560	\$105,506,000	\$946,350	\$7,200,000,000.00	\$7,200,000,000.00
45,359	30	\$32,658,480	\$381,015,600	\$1,055,060,000	\$9,463,500	\$72,000,000,000.00	\$72,000,000,000.00

Production Rate (kg/hr)	Days of Storage (days)	Depreciation (\$/yr)	Annual Electricity Cost (\$/yr)	Annual Cooling Water Cost (\$/yr)	Total Annual Cost (\$/yr)	Capital Cost (\$/kg)	Energy Cost (\$/kg)	Cooling Cost (\$/kg)	Total Cost (\$/kg)
5	1	\$10,909	\$3,360	\$147	\$14,416	\$0.29	\$0.09	\$0.00	\$0.38
45	1	\$109,091	\$33,600	\$1,470	\$144,161	\$0.29	\$0.09	\$0.00	\$0.38
454	1	\$1,090,909	\$336,000	\$14,700	\$1,441,609	\$0.29	\$0.09	\$0.00	\$0.38
4,536	1	\$10,909,091	\$3,360,000	\$147,000	\$14,416,091	\$0.29	\$0.09	\$0.00	\$0.38
45,359	1	\$109,090,909	\$33,600,000	\$1,470,000	\$144,160,909	\$0.29	\$0.09	\$0.00	\$0.38
5	2	\$21,818	\$3,360	\$147	\$25,325	\$0.57	\$0.09	\$0.00	\$0.66
45	2	\$218,182	\$33,600	\$1,470	\$253,252	\$0.57	\$0.09	\$0.00	\$0.66
454	2	\$2,181,818	\$336,000	\$14,700	\$2,532,518	\$0.57	\$0.09	\$0.00	\$0.66
4,536	2	\$21,818,182	\$3,360,000	\$147,000	\$25,325,182	\$0.57	\$0.09	\$0.00	\$0.66
45,359	2	\$218,181,818	\$33,600,000	\$1,470,000	\$253,251,818	\$0.57	\$0.09	\$0.00	\$0.66
5	4	\$43,636	\$3,360	\$147	\$47,143	\$1.15	\$0.09	\$0.00	\$1.24
45	4	\$436,364	\$33,600	\$1,470	\$471,434	\$1.15	\$0.09	\$0.00	\$1.24
454	4	\$4,363,636	\$336,000	\$14,700	\$4,714,336	\$1.15	\$0.09	\$0.00	\$1.24
4,536	4	\$43,636,364	\$3,360,000	\$147,000	\$47,143,364	\$1.15	\$0.09	\$0.00	\$1.24
45,359	4	\$436,363,636	\$33,600,000	\$1,470,000	\$471,433,636	\$1.15	\$0.09	\$0.00	\$1.24
5	7	\$76,364	\$3,360	\$147	\$79,871	\$2.00	\$0.09	\$0.00	\$2.10
45	7	\$763,636	\$33,600	\$1,470	\$798,706	\$2.00	\$0.09	\$0.00	\$2.10
454	7	\$7,636,364	\$336,000	\$14,700	\$7,987,064	\$2.00	\$0.09	\$0.00	\$2.10
4,536	7	\$76,363,636	\$3,360,000	\$147,000	\$79,870,636	\$2.00	\$0.09	\$0.00	\$2.10
45,359	7	\$763,636,364	\$33,600,000	\$1,470,000	\$798,706,364	\$2.00	\$0.09	\$0.00	\$2.10
5	14	\$152,727	\$3,360	\$147	\$156,234	\$4.01	\$0.09	\$0.00	\$4.10
45	14	\$1,527,273	\$33,600	\$1,470	\$1,562,343	\$4.01	\$0.09	\$0.00	\$4.10
454	14	\$15,272,727	\$336,000	\$14,700	\$15,623,427	\$4.01	\$0.09	\$0.00	\$4.10
4,536	14	\$152,727,273	\$3,360,000	\$147,000	\$156,234,273	\$4.01	\$0.09	\$0.00	\$4.10
45,359	14	\$1,527,272,727	\$33,600,000	\$1,470,000	\$1,562,342,727	\$4.01	\$0.09	\$0.00	\$4.10
5	30	\$327,273	\$3,360	\$147	\$330,780	\$8.59	\$0.09	\$0.00	\$8.68
45	30	\$3,272,727	\$33,600	\$1,470	\$3,307,797	\$8.59	\$0.09	\$0.00	\$8.68
454	30	\$32,727,273	\$336,000	\$14,700	\$33,077,973	\$8.59	\$0.09	\$0.00	\$8.68
4,536	30	\$327,272,727	\$3,360,000	\$147,000	\$330,779,727	\$8.59	\$0.09	\$0.00	\$8.68
45,359	30	\$3,272,727,273	\$33,600,000	\$1,470,000	\$3,307,797,273	\$8.59	\$0.09	\$0.00	\$8.68

5.1.4. Delivery



A key element of the overall hydrogen energy infrastructure is the delivery system that moves the hydrogen from its point of production to an end-use device. At present, hydrogen is produced in a limited number of plants and is used for making chemicals or upgrading fuels. It is currently transported by pipeline or by road via cylinders, tube trailers, and cryogenic tankers, with a small amount shipped by rail car or barge.

As is the case of natural gas distribution, pipelines are employed as an efficient means to supply customer needs. The pipelines are currently limited to a few areas of the United States where large hydrogen refineries and chemical plants are concentrated. Concerns regarding the weakening of carbon steel pipes in a process called hydrogen embrittlement are being addressed.

Hydrogen distribution via high-pressure cylinders and tube trailers has a range of 100 to 200 miles from the production or distribution facility. For long-distance distribution of up to 1,000 miles, hydrogen is usually transported as a liquid in super-insulated, cryogenic, over-the-road tankers, railcars, and barges and is then vaporized for use at the customer site. The method selected for distribution depends not only on the distance transported, but also on the production method and/or end use.

5.1.4.1. Transportation

A combination of these three options (cryogenic liquid trucks, compressed tube trailers, and gaseous pipelines) could be used during various stages of hydrogen fuel market development.

- Tube trailers could be used during the initial introductory period because the demand probably will be relatively small and it would avoid the boil-off incurred with liquid hydrogen storage.
- Cryogenic tanker trucks could haul larger quantities than tube trailers to meet the demands of growing markets.
- Pipelines could be strategically placed to transport hydrogen to high demand areas, as more production capacities are placed on-line.

5.1.4.1.1. Compressed Gas Transportation

Compressed gas can be transported using high-pressure cylinders, tube trailers or pipelines. If hydrogen is to be transported as a gas, it should be compressed it to a very high pressure to maximize tank capacities. High-pressure gas cylinders for example are rated as high as 40 MPa (5,800 psig) and hold about 1.8 kg (4 lb) of hydrogen, but are very expensive to handle and transport. Tube trailers, consisting of several steel cylinders mounted to a protective framework, can be configured to hold 63-460 kg (140-1,000 lb) of hydrogen, depending on the number of tubes. Operating pressures are 20-60 MPa (2,900-8,700 psig). Hydrogen is delivered by pipeline in several industrial areas of the United States, Canada, and Europe. Typical operating pressures are 1-3 MPa (145-435 psig) with flows of 310-8,900 kg/h (685-20,000 lb/h). The United States has more than 720 km (447 mi) of hydrogen pipelines concentrated along the Gulf Coast and Great Lakes.

Hydrogen Transport as a Compresses Gas via Truck

Trip Distance (km)	Quantity Transported (GJ/yr)	Typ. Cap. Invest. (\$/GJ)	Transport Cost (\$/GJ)
16	0.458 – 45.8MM	4.10	4.70
161	0.458 – 45.8MM	8.20	10.60
322	0.458 – 45.8MM	13.7 – 16.4	18.30 – 18.60
805	0.458 – 45.8MM	30.20	41.10
1,609	0.458 – 45.8MM	57.60	79.10 – 79.70

5.1.4.1.2. Liquid Hydrogen Transport

Liquid hydrogen is transported using special double-walled insulated tanks to prevent boil-off of the liquid hydrogen. Some tankers also use liquid nitrogen heat shields to cool the outer wall of the liquid hydrogen vessel to further minimize heat transfer. Tank trucks can carry 360-4,300 kg (800-9,500 lb) of liquid hydrogen. Railcars have even greater capacities, carrying 2,300-9,100 kg (5,000-20,000 lb) of hydrogen. Boil-off rates for trucks and railcars are 0.3%-0.6%/day. Barges or sea-going vessels have been considered for long-distance transport of hydrogen.

One other idea for the delivery of liquid hydrogen is through an insulated pipeline that would also include a super-conducting wire. The liquid hydrogen would act as a refrigerant for the superconductor and would allow long distance transportation of electricity without the high current losses of conventional power lines. The main problem with liquid hydrogen transport would be the specialized insulating requirements and losses from pumping and re-cooling the liquid hydrogen along the way.

5.1.4.1.3. Metal Hybrid Transport

Metal hydrides can be used for transport by absorbing hydrogen with a metal hydride, then loading the entire container onto a truck or railcar for transport to the customer's site where it can be exchanged for an empty hydride container, or used as a conventional tanker.

5.1.4.2. Delivery

5.1.4.2.1. Road Delivery

Delivery by cryogenic liquid hydrogen tankers is the most economical pathway for medium market penetration. They could transport relatively large amounts of hydrogen and reach markets located throughout large geographic areas. Tube trailers are better suited for relatively small market demand and the higher costs of delivery could compensate for losses due to liquid boil-off during storage. However, high-pressure tube trailers are limited to meeting small hydrogen demands.

Typically, the tube-to-hydrogen weight ratio is about 100-150:1. A combination of low gaseous hydrogen density and the weight of thick wall, high quality steel tubes (80,000 pounds or 36,000 kilograms) limit each load to 300 kilograms of hydrogen. In reality, only 75%-85% of each load is dispensable, depending on the dispensing compressor configuration. Unlike tanker trucks that discharge their load, the tube

and undercarriage are disconnected from the cab and left at the fueling station. Tube trailers are used not only as transport container, but also as on-site storage. As a result, the total number of tubes provided equals the number of tubes left at the fueling stations and those at the central plants to be picked up by the returning cabs.

Hydrogen Transport as a Liquefied Gas via Truck

Trip Distance (km)	Typ. Cap. Invest. (\$/GJ)	Transport Cost (\$/GJ)
16	0.44 – 11.0	0.24 – 1.60
161	0.77 – 11.0	0.52 – 1.84
322	2.20 – 11.0	1.00 – 2.20
805	2.70 – 11.0	2.00 – 3.10
1,609	5.10 – 11.0	3.90 – 4.70

5.1.4.2. Pipeline Delivery

Pipelines are most effective for handling large flows. They are best suited for short distance delivery because pipelines are capital intensive (\$0.5 to \$1.5 million/mile). Much of the cost is associated with acquiring right-of-way. Currently, there are 10,000 miles of hydrogen pipelines in the world. At 250 miles, the longest hydrogen pipeline connects Antwerp and Normandy. Operating costs for pipelines are relatively low. To deliver hydrogen to the fueling stations at 30 atmospheres, the pressure drop could be compensated with either booster compressors or by compressing the hydrogen at the central plant.

5.1.4.3. Capital Costs of Transportation Equipment

5.1.4.3.1. Compressed Gas Road Transport Costs

Tube trailer capital costs depend on the operating pressure of the truck, the storage capacity of each trailer, and the distance to the customer site. Higher operating pressures increase the capacity of a tube trailer, but increase the purchased price of each truck. This can result in lower overall capital costs by reducing the number of trucks required. The distance to the customer site also affects the number of trucks. For local delivery, the same truck can make several trips back and forth between the production site and the customer site, but for long distances, each truck might be able to make only one or two deliveries per day. One capital cost of \$340,000 was found for a tube trailer containing 16 tubes with a total capacity of 460 kg (1,000 lb) of hydrogen. The cost of a truck cab to go with it was \$110,000. Operating costs include fuel costs and driver wages or freight charges.

5.1.4.3.2. Compressed Gas Pipeline Transport Costs

Hydrogen pipelines are constructed of 0.25-0.30 m (10-12 in.) commercial steel and operate at 1-3 MPa (145-435 psig). Natural gas mains for comparison are constructed of pipe as large as 2.5 m (5 ft) in diameter and have working pressures of 7.5 MPa (1,100 psig). Because a large fraction of the pipeline cost is for installation, natural gas construction prices were used to estimate the pipeline costs.

The major operating cost for hydrogen pipelines is compressor power and maintenance. Some hydrogen losses may occur in the piping network, but for natural gas piping systems, these losses are less than 1%. An estimate for the United States puts the cost at \$0.39/kg (\$0.18/lb).

For large quantities of hydrogen, pipelines are the cheapest means of transporting hydrogen, except for transport across the ocean, when liquid hydrogen transport is the cheapest means.

5.1.4.3.3. Liquid Hydrogen Road Transport Costs

The capital costs of liquid hydrogen transport will consist mainly of the insulated tank trailer or railcar, plus the cost of the cab for truck transport. The liquid hydrogen truck transport costs include the same fuel, driver wages and maintenance charges as for gas transport, but also include boil-off losses during transport. Expected boil-off losses during transfer between tanks is 10%-20%, but can be as high as 50%. As mentioned earlier, boil-off during transport is expected to be 0.3%-0.6%/day. Railcar transport of hydrogen includes boil-off losses during transport and transfer, plus rail freight charges.

5.1.4.3.4. Metal Hybrid Road Transport Costs

For transportation of hydrogen using metal hydrides, the major cost is the capital expense of buying the metal hydride and containers. Once filled, the hydride containers can be shipped like any other piece of freight, with charges depending on the distance and weight.

Hydrogen Transport via Truck in Metal Hydrides

Trip Distance (km)	Quantity Transported (GJ/yr)	Typ. Cap. Invest. (\$/GJ)	Transport Cost (\$/GJ)
16	0.458 – 45.8MM	7.54	2.63
161	0.458 – 45.8MM	15.08	5.75
322	0.458 – 45.8MM	25.13	9.80
805	0.458 – 45.8MM	55.28	21.92
1,609	0.458 – 45.8MM	105.54	42.11

5.1.4.4. Choice of Transportation

The main factors affecting the choice of hydrogen transport are the application, quantity, and distance from the production site to the customer.

5.1.4.4.1. Quantity

For large quantities of hydrogen, pipeline delivery is cheaper than all other methods. The next cheapest method of delivery would be liquid hydrogen. Pipeline delivery has the benefit of a very low operating cost, consisting mainly of compressor power costs, but has a high capital investment. Liquid hydrogen, on the other hand, would have a high operating cost, but possibly a lower capital cost, depending on the quantity of hydrogen and the delivery distance. The break-even point between liquid hydrogen and a pipeline will vary depending on the distance and quantity.

For smaller quantities of hydrogen, pipeline delivery is not competitive, but compressed gas delivery may be competitive. Compared to liquid hydrogen, compressed gas has lower power requirements and slightly lower capital costs for the tube trailers, but many more tube trailers are required to deliver the same quantity of hydrogen. Which delivery method is more economical will depend on the delivery distance, because it may be possible to use the same tube trailer for several trips per day if it is a short distance.

For still smaller quantities, the high capital cost of a pipeline eliminates it as an option. The deciding factor between liquid hydrogen and compressed gas becomes a matter of distance. For long distances, the higher energy costs of liquefaction will balance out against the higher capital and transportation expense of many compressed gas tube trailer trips back and forth. If the distance is relatively short, and the quantity of hydrogen transported is small, compressed gas may win out.

Metal hydride transport costs tend to fall between those for liquid hydrogen transport and compressed gas transport. While metal hydride transport has a larger

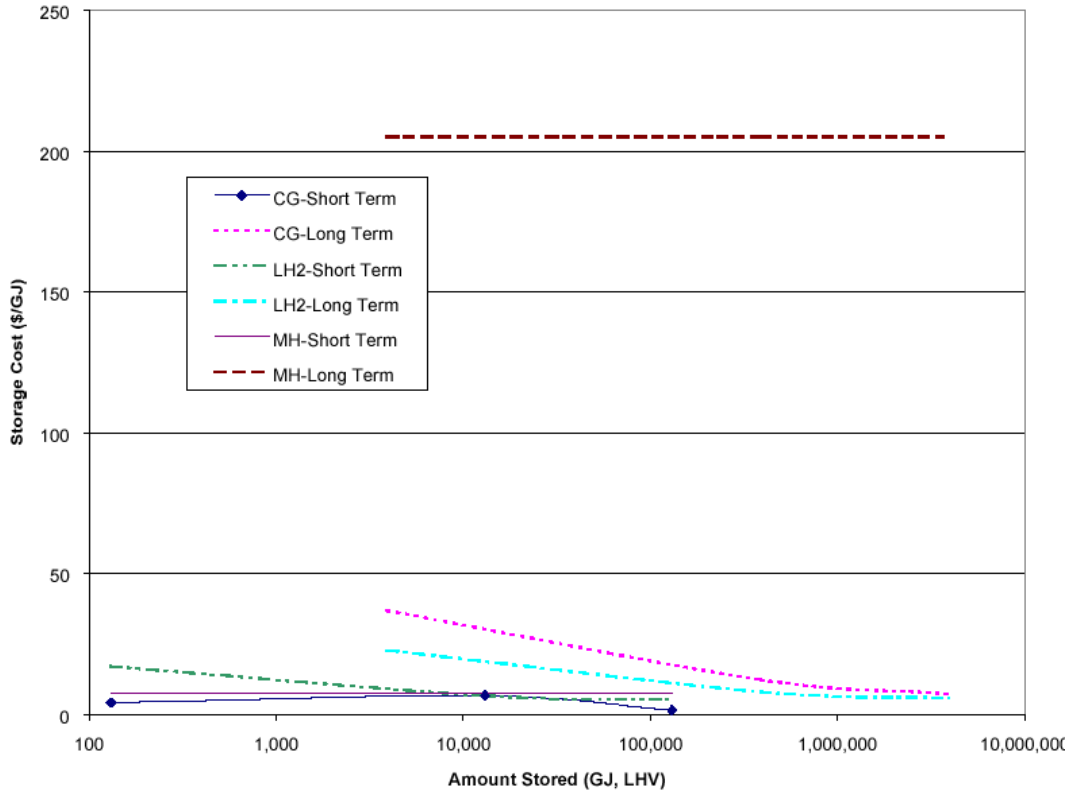
capital expense per truck, the hydrogen capacity per truck is greater compared to using compressed gas transport.

5.1.4.4.2. Distance

Distance is an important factor. For a short distance a pipeline can be very economical because the capital expense of a short pipeline may be close to the capital cost of tube trucks or tankers, and there are no transportation or liquefaction costs. As the distance increases, the capital cost of a pipeline increases rapidly, and the economics will depend on the quantity of hydrogen-- pipelines will be favored for larger quantities of hydrogen. For small quantities of hydrogen, at some point the capital cost of the pipeline will be higher than the operational costs associated with delivering and liquefying the hydrogen.

Distance is a deciding factor between liquid and gaseous hydrogen. At long distances, the number of trucks required to deliver a given quantity of compressed hydrogen will be greater than the increased energy costs associated with liquefaction and fewer trucks.

Hydrogen Transport Cost for Varying Distances



5.1.4.4.3. Power Supply

One special case related to hydrogen is when energy must be transmitted a long distance. Currently, energy is transmitted by high-voltage power lines, and current losses result in a 7%-8% loss in transmitted energy. Hydrogen gas transport through a pipeline on the other hand, results in somewhat lower losses, meaning it may be cheaper to produce hydrogen and pipe it to a location requiring heat or electrical energy because the energy losses are less with a hydrogen pipeline. One source indicated the cutoff where hydrogen energy transport is cheaper than overhead lines is 1,000-2,250 km (631-1,398 miles).

5.1.4.4.4. Summary

Below is a summary of the decision making criteria:

- Pipeline - For large quantities or long-distance power transmission.
- Liquid Hydrogen - For transport over long distances.
- Compressed Gas - For small quantities over short distances.
- Metal Hydride - For short distances.

5.1.4.5. Challenges

A complete delivery infrastructure for hydrogen faces numerous engineering, environmental, institutional, and market challenges. Since fueling economics depend on volume, the chicken and egg dilemma impedes the installation of an effective infrastructure. There is no simple reconciliation between the level of investments required to achieve low costs and the gradual development of the market. Current investments in delivery systems need to be justifiable beyond 2020 to support adequate returns on investment.

5.1.4.6. Conclusions

Liquid hydrogen transport by truck is the cheapest alternative, except for large quantities of hydrogen, when pipeline delivery becomes competitive. At longer distances, the capital cost of the extra pipeline requires more hydrogen flow before it will compete with liquid hydrogen delivery. Sharing the expense of a pipeline among several suppliers and users would reduce these costs. Because the major expense

is installing the pipeline, and not the pipeline cost itself, a larger pipeline can be installed to handle multiple users for about the same cost.

Very little energy is required to pump the hydrogen through the pipeline. Bringing the hydrogen up to pressure would require a great deal more energy. These power requirements were incorporated into the previous storage costs. In all cases, except pipeline delivery, a minimum transport cost is associated with each delivery method for a given distance. This point is reached when the production rate is high enough that the truck or rail car is being fully utilized 100% of the time. As an example, a small hydrogen plant doubles its production rate and, instead of making one trip per day with a liquid hydrogen truck, it makes two trips per day. The total capital cost remains the same--the cost of one truck--but this cost is now spread out over twice as much hydrogen. If a truck is already fully utilized, however, any increase in production will require purchasing another truck and produces no reduction in transport costs. The lowest capacity methods level off first for any given distance as production rate increases.

Rail car costs vary little with production rate and distance; railcars quickly become fully utilized because of the long transit times associated with rail transport--they spend most of their time in transit or sitting in a rail yard. This results in high capital costs for many of rail cars, but the flat shipping rate makes rail transport charges insensitive to distance. Liquid transport by rail is almost as cheap as truck liquid transport and is cheaper than the other trucking options because of the large capacity per railcar.

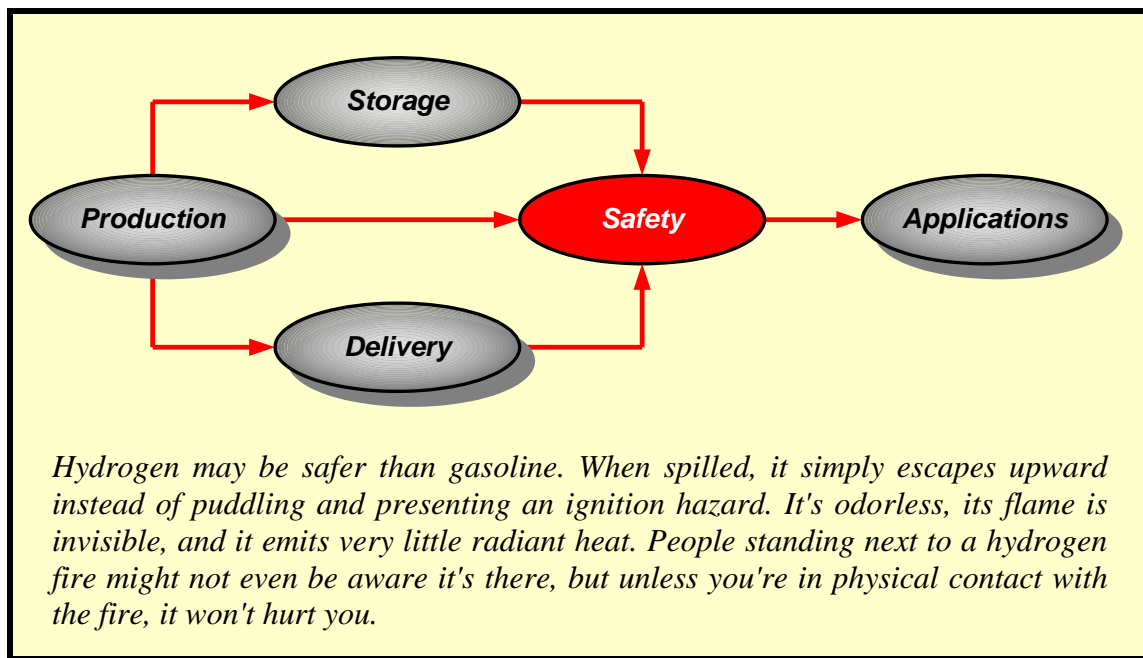
As expected, the truck transport costs increase with distance because of the higher labor and fuel costs. Capital costs also increase with distance. For short distances, one truck can make multiple trips each day, but as the distance increases, more trucks are needed because more time is spent in transit—there is less chance to use the same truck for multiple trips. Compressed gas transport is affected the most - it requires the most trips because of the low hydrogen capacity per truck. For all methods, labor costs quickly start to dominate for distances longer than 160 km (100 mi).

Compressed gas delivery costs also see the largest effect from fuel price because of the many trips. For small production rates, liquid hydrogen transport costs are high because the truck is not fully utilized, it may only make a few trips per week. At these low flows, the truck capital cost contribution is the largest cost, but the costs are also less sensitive to distance because there are far fewer trips compared to larger production rates. At all flow rates, as distance increases, liquid hydrogen delivery charges become dominated by the labor costs. However, with liquid hydrogen, the effect is small compared to compressed gas because the driver is carrying more hydrogen per trip. One hydrogen tanker can carry more than 20 times the amount of hydrogen as a tube trailer.

At a medium production rate of 450 kg/h (1,000 lb/h) and a 160 km (100 mi) delivery distance, liquid hydrogen trucking was the cheapest means of transport, but metal hydride also competes because of its high storage density. To illustrate the effect of truck capacity for each delivery method, at the above production rate and delivery distance, 15 tube trailers would be needed, making 60 trips per day (four trips per truck), six hydride trucks making 24 trips per day (four trips per truck) or one liquid hydrogen truck making three trips per day.

The increased weight of the metal hydride was not taken into account when analyzing the transportation costs. Also, there is a great difference in capital expenditures required among the different transport methods. For the above example, the price of one liquid hydrogen tanker with cab is \$500,000, the price of 15 tube trailers with cabs is about \$3.75 million, and the price of six metal hydride transports is \$6.9 million to transport the same amount of hydrogen the same distance.

5.1.5. Safety



Hydrogen fuel has had an ill-fated reputation due to the major accidents of the Hindenburg dirigible and the 1986 Challenger shuttle explosion. Although neither of these disasters was directly caused by the use of hydrogen, they have contributed to the misconception of hydrogen safety. It is commonly overlooked that safe uses of hydrogen fuel have been occurring at NASA since the 1960's and for nearly 80 years in Germany.

With the potential for the transition to a hydrogen-based economy, safety concerns and precautions need to be made in production, transportation, and storage. Currently the *1998 Sourcebook for Hydrogen Applications*, funded by the US Department of Energy and the Natural Resources Canada, serves as an interim guide for hydrogen production and use while the International Organization of Standards is developing an international set of standards and codes. The current standards under development are shown in the table to the right.

Despite the common misconceptions, hydrogen is hard to characterize in relative safety to other fuels such as gasoline. An analysis by Argonne National Laboratory found hydrogen safety advantages are low-spill probability in collisions, more rapid dispersal when spilled than gasoline, relatively high lower flammability limit (4%

compared to 1% for gasoline) and when ignited, hydrogen's low emissivity reduces the risk of secondary materials igniting. However in the same report, it is stated that hydrogen has a risk of explosion when stored under pressure due high-pressure requirements (~6000 psi) and has a greater likelihood of exploding. It has a high flammability, high heat emissivity, and heavier-than-air vapor. Hydrogen has a burning velocity that is seven times greater than gasoline but when for the same amount of fuel, hydrogen explosions have 20 times less energy than an explosion of gasoline vapor.

Leak and fire detection of hydrogen fuel is imperative because hydrogen is colorless and odorless and since hydrogen flame is not visible to the eye in daylight. This causes a high risk for thermal burns when contacting flames or asphyxiation in enclosed areas during accidents. The possibility of adding an odorant or colorant to hydrogen fuel is being considered but further investigated is needed to determine effects on the purity of hydrogen fuel and on the hydrogen liquefaction process. Also, an odorant or colorant would not aid in the detection of hydrogen fires. Another precaution to be taken is that fueling stations and storage sites need to be

International Standards already published are:

- ISO 13984: Liquid hydrogen – Land vehicle fueling system interface
- ISO 14687: Hydrogen fuel – Product specification

Standards under development:

- ISO/CD 13985: Liquid hydrogen – Land vehicle fuel tanks
- ISO/WD 13986: Tank containers for multi-modal transportation of liquid hydrogen
- ISO/WD 15594: Airport hydrogen fueling facility
- ISO/WD 15866: Gaseous hydrogen blends and hydrogen fuel – Service stations
- ISO/WD 15869: Gaseous hydrogen and hydrogen blends – Land vehicle fuel tanks
- ISO/WD 15916: Basic requirements for the safety of hydrogen systems
- ISO/AWI 17268: Gaseous hydrogen – Land vehicle fueling connectors

Source: International Organization for Standards, Committee of Hydrogen Technologies

equipped with dry chemical extinguishers and an integrated control system with emergency shutoffs.

Hydrogen presents one of the greatest fire hazards of fuels due to its wide flammability limits in air, 4-75 vol-%, and its low ignition temperature, 585°C. However hydrogen has a very low density and dissipates quickly, reducing the risk of fire hazards in ventilated areas. The following table shows order of preference for storage location of hydrogen fuels based on the hazardous materials code 29 CFR 1910.103 (1996) and National Fire Protection Agency Code 50A (1994). The table also shows that the ideal storage is outside and away from any occupancies or equipment.

Order of Preference of Storage Location of Hydrogen*

Nature of Location	Gaseous H ₂ Volume (m ³)			Liquid H ₂ Volume (Liters)			
	< 85	85 to 425	> 425	150 to 189	190 to 1136	1137 to 2271	> 2271
Outdoors	I	I	I	I	I	I	I
In separate building	II	II	II	II	II	II	Not Permitted
In special room (inside building)	III	III	Not Permitted	III	III	Not Permitted	Not Permitted
Inside buildings, but not in special room and exposed to occupancies	IV	Not Permitted	Not Permitted	IV	Not Permitted	Not Permitted	Not Permitted

*Ranked in order of preference with Roman numeral 1 indicating most preferred
Sources: 29 CFR 1910.103 and NFPA 50a & 50B

In vehicles, storage vessels must be designed to minimize risks during collisions, and maintain the high pressures needed to compress the fuel. Since hydrogen does dissipate quickly, initial safety evaluations have found hydrogen less dangerous than other fuels during accidents but further research is still being conducted. Compressed hydrogen tanks are tested rigorously by the Department of Transportation to meet standards for transportation. For example, composite 10,000 psi (~70 MPa) tanks have to demonstrate a safety factor of 2.35 (23,500 psi burst pressure) as required by the European Integrated Hydrogen Project.

Fire Hazard Properties of Hydrogen, Gasoline, and Methane

Property	Gasoline	Methane	<i>Hydrogen</i>
Physico-Chemical Properties			
Density (kg/m ³)	4.40	0.65	0.084
Diffusion Coefficient In Air (cm ² /sec)	0.05	0.16	0.610
Specific Heat at Const. Pressure (J/Gk)	1.20	2.22	14.89
Ignition Limits In Air (vol %)	1.0-7.6	5.3-15.0	4.0-75.0
Ignition Energy In Air (MJ)	0.24	0.29	0.02
Ignition Temperature (°C)	228-471	540	585
Flame Temperature In Air (°C)	2197	1875	2045
Explosion Energy (G TNT/kJ)	0.25	0.19	0.17
Flame Emissivity (%)	34-43	25 -33	17-25
Emergency Response Guidance			
Immediate Spill Isolation Distance (m)	25-50	NA	50-100
Large Spill Evacuation Distance (m)	300	NA	50-100
Tanker Fire Isolation Distance (m)	800	NA	1600

Liquid hydrogen storage for on-board use is attractive since it is more compact than compressed hydrogen. However, the cryogenic containers must be maintained at minus 253.2°C, a temperature that can instantly freeze skin and air. The low temperatures create a risk for frozen valves; this situation has caused accidents from the resulting pressure buildup. On-board storage of hydrogen in metal hydrides is one of the safest methods of transporting hydrogen but emits high heats of reaction (9300-20,000 kJ/kg of hydrogen) during hydrogen release, causing temperatures of nearly 500°C and in certain circumstances metal hydride tanks can reach extremely high pressure during release (10kPa). Alternative storage devices such as carbon nanotubes and glass microspheres are in development and are potentially safe options for on-board hydrogen fuel storage. These new devices for storage are still in development and the safety of their use is not well tested.

Transport of hydrogen by pipeline is a potential possibility for long distance transport of hydrogen. Germany has been operating a 210 km, 25cm-diameter stainless steel pipeline since 1939 with no serious accidents. Air Liquide and runs operate the longest pipeline in the world 400 km from Northern France to Belgium. These lines carry compressed gas and have typical operating conditions of pressures in the range of 1-3 MPa with flows of 310-8900 kg/hr. Liquid hydrogen can also be transported by insulated pipeline that is cooled by super-conducting wire.

Despite the potential for losses by dissipation, the most prominent concern for pipeline transport is metal embrittlement. It has been suggested that hydrogen can be transported through existing natural gas pipelines but major modifications need to be made to welding, seals, and fittings to prevent embrittling and surface cracking of

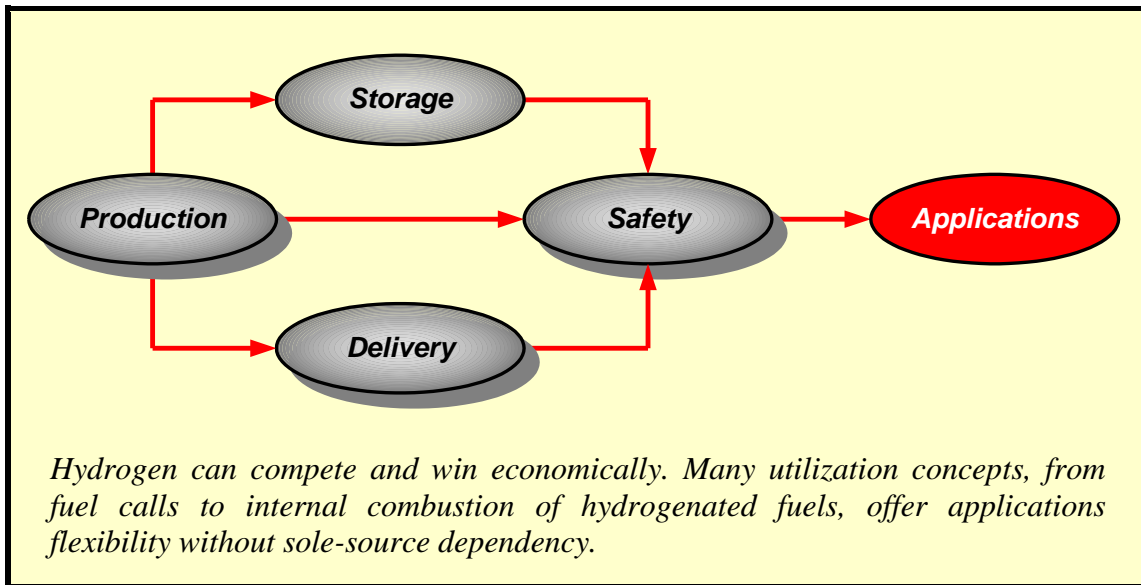
pipes and to handle extremely high pressures needed to transport hydrogen. The ideal material for gaseous hydrogen storage and transport is aluminum, which has only slight susceptibility to hydrogen. Other materials deemed compatible for compressed hydrogen are Teflon (for valve seats, soft coatings on metallic O-rings, and some gaskets) and ordinary carbon steels. Cast iron and some steels have shown great susceptibility to hydrogen embrittlement. For example, unstabilized austenitic stainless steel (300 series) has been found to revert to martensitic steel, reducing the ductility of the metal. As a result iron, low alloy steels, chromium and most body-centered cubic crystal structures cannot be used for hydrogen fuel storage and transport.

Embrittlement of metals increases with increased hydrogen purity and increased extremity of operating temperature. For liquid hydrogen transport nickel steels with 3.5, 5, or 9% nickel are considered satisfactory depending on temperature. For temperatures below 76 K (-323°C) only 9-nickel steel can be used. An unfortunate example of low temperature embrittlement by liquid natural gas (LNG) occurred in Cleveland in 1944. A storage vessel made of 3.5% nickel steel with a capacity of 4248 m³ ruptured and released 4163 m³ of LNG into near by storm sewers. It ignited and caused other vessels to rupture. There were nearly 400 injuries, 128 deaths, and \$6.8 million in property damage.

The surface of the storage vessel must be smooth since trapping sites and pores increase susceptibility of metal embrittlement. In all hydrogen environments, welds and seals are prone to cracking and embrittlement. Post weld annealing is necessary to prevent residual stresses and hard spots and to restore a favorable microstructure of the surface. Considerations also need to be made for contraction and expansion. The temperature span from ambient to cryogenic temperatures is about 200 K (360°F), which will result in significant thermal contraction of most materials.

As with gasoline and methane, proper safety precautions need to be made with hydrogen fuel. Detection of leaks and fires are key to ensuring safe storage and transport of hydrogen fuel. Materials of construction for storage vessels and transport (both for commercial and for on-board use) are necessary considerations for proper safety during collisions. Consumer education and awareness is an important step in the transition to a hydrogen-based economy. As improvements are made in the safety of hydrogen, a feasible hydrogen economy can rapidly evolve.

5.1.6. Applications



A new future in automotive transportation is steadily approaching. This future will be one in which light and heavy vehicles are powered by new clean and efficient energy sources. While many technologies will contribute to this future, many see the fuel cell as the leading long-term candidate for becoming the power source for petroleum- and emissions-free, mass-produced light vehicles, as well as some types of heavy vehicles. While the successful resolution of remaining technical and economic barriers to fuel cell vehicles is not a foregone conclusion, success is closer than ever before.

5.1.6.1. Fuel Cells

At this point in time, fuel cell vehicles promise the best opportunity to achieve a net-zero carbon energy and emissions future for the automotive mass market. They would deliver high-energy efficiency possibly up to twice that of gasoline-powered internal combustion engines, since hydrogen possesses the highest energy content per unit weight of any known fuel (120.7 kJ/g). They would offer near-zero levels of air pollution and greenhouse gas emissions. They could be made small enough to fit compactly in vehicles, yet strong enough to produce power equivalent to that of gasoline-powered. And, unlike pure electric vehicles, they could provide a sufficient driving range without needing downtime for recharging.

Most important, the use of fuel cells for an application as complex and demanding, as vehicles would provide a major paradigm shift in global energy consumption and supply. The potential would exist to create new industries and

allow people throughout the global community to enjoy the benefits of access to an efficient, cost-effective, and reliable energy source. Thus, the new hydrogen automotive future could have a global economic impact far beyond the automotive sector itself, both in terms of the automotive industry's effect on overall economic world growth and as the driver of an enabling technology applicable to many sectors and industries.

Hydrogen's potential use in fuel and energy applications includes powering vehicles, running turbines or fuel cells to produce electricity, and generating heat and electricity for buildings.

5.1.6.2. Fuel Cell Applications

In theory, a fuel cell can power anything that runs on electricity. The following applications can take particular advantage of a fuel cell's attributes.

5.1.6.2.1. Cars, Trucks, and Buses

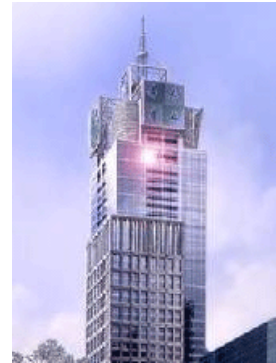
Most vehicles today rely on an internal combustion engine (ICE) that burns fossil fuels to generate motive force. The ICE is also a poor fit to the demands of a vehicle. Electric motors are much more suitable because they deliver their maximum torque at low rpm, just when a vehicle needs it most. And when a driver heads downhill or puts on the brakes, an electric motor can double as a generator to recapture that energy and convert it back to electricity for subsequent use.



Unfortunately, the short range and tedious recharging of the 1st generation, battery-powered electric cars have tainted the notion of an electrical vehicle in the public eye. But these problems can be overcome when a fuel cell powers the vehicle's electric motor. A hydrogen tank can be refueled in about five minutes, and has a similar range to a conventional automobile. While handling hydrogen gas requires specific precautions, it is just as safe to fuel your car with hydrogen as with gasoline or natural gas.

5.1.6.2.2. Businesses and Homes

Fuel cells are attractive in stationary applications for a variety of reasons. They deliver unparalleled fuel efficiencies, especially in Combined Heat & Power (CHP) applications where the waste thermal energy is harvested for HVAC or industrial purposes. The Durst building at 4 Times Square, New York, NY, employs fuel cells to power its base load with these benefits in mind. In addition, their fuel cells offer a new level of reliability: if a blackout occurs, they will keep essential mechanical components and external landmark signage online. This assurance of highly reliable power led The First National Bank of Omaha to run their mission-critical credit card transaction unit with fuel cells. Their managers know that blackouts aren't just annoying—they're expensive. Hewlett-Packard estimated that a fifteen-minute outage at one chip fabrication plant would cost the company \$30 million, or half the plant's power budget for an entire year. In addition to clean, quiet operation, fuel cells offer highly reliable, high-quality electricity.



5.1.6.2.3. Laptops, Cell Phones, and other Electronics

Fuel cells will find their first widespread use in portable electronics. These "micro fuel cells" offer far higher energy densities than those of comparably sized batteries, allowing a typical laptop to operate unplugged for ten hours or more. Micro fuel cells also offer the added appeal of eliminating the need for battery chargers and AC adapters, as they require refueling instead of recharging. This process could be done via "hot-swapping" whereby the device does not need to be turned off to get a new full tank of energy.

5.1.6.2.4. An Example: First National Bank of Omaha

Contingency Planning Research estimates that power fluctuations cause 45 percent of all computer data losses and the Electric Power Research Institute estimates that power-quality breakdowns caused some \$50 billion in business losses in 1999. However, most high yield facilities can't afford to surrender floor space to back up power systems that earn no revenue. Web hosting centers, for instance, can generate more than \$1,000 a year per square foot of rental space.

There is a solution to this apparent dilemma: 'high availability' power systems that economically replace the common 'grid + diesel + battery' back-up power strategy with a distributed primary power system (including fuel cells in some

configurations, as well as gas turbines, flywheels and other technologies). Placed adjacent to, but outside, the facilities they power, these systems free up a tremendous amount of highly profitable floor space that batteries and UPS (uninterruptible power supply) systems would occupy.



Fuel Cell installation at FNBO

In 1999, the First National Bank of Omaha (FNBO)—the nation’s largest privately owned bank—installed a \$3.4-million, 800-kw fuel-cell system as the primary power source for its new 200,000 square foot Technology Center’s critical loads. FNBO had previously endured power outages where even its back-up systems failed. The fuel cell system they installed provides the first ever ‘Seven 9’s’ (99.99999% available) power system in such a setting.

As the nation’s seventh largest credit card trans-action processor, handling over three million transactions per day, 365 days a year, FNBO simply can’t afford power outages." A single one-hour blackout could cost FNBO’s credit-card operation as much as \$6 million in lost business," according to Business Week.

Faced with such vulnerabilities, this system emerged as a cost competitive solution for their critical load applications. Over a 20-year life span, fuel cells are "the cheapest way to go," the bank’s director of property management, Dennis C. Hughes told Business Week.

5.1.6.3. Conclusions

5.1.6.3.1. Agreement on Public Interest

It is apparent that most nations have accepted that support for and acceleration of the adoption of fuel cell technologies is in the public interest. The most common reasons cited for believing that fuel cell development is in the public interest are the possibilities of cutting CO₂ and other harmful emissions, reducing dependency on petroleum, and enhancing industrial competitiveness. Despite the public need for a cleaner environment, less dependency on petroleum, and the economic benefits derived from a strong automotive sector, however, the market will not be able to make the transition by itself, given current fuel prices and infrastructure requirements. Accordingly, there is also a consensus that a public policy role exists.

For the most part, public policies are geared toward helping domestic companies—vehicle manufacturers and component suppliers—be ready to (1) commercially produce mass transit vehicles, niche market vehicles, and light

vehicles and (2) play a role in a globally competitive market by around 2010 to 2015. Considerably less attention has been paid to issues relating to the hydrogen infrastructure needed to supply the vehicles, although demonstrations of fueling stations are beginning and strategic planning is under way. These efforts are expanding in terms of scope, size, and the number of countries involved.

5.1.6.3.2. The current Global Situation

The current global situation is extremely competitive. Because of the continuing importance of the automotive industry to the economies of many countries, it is seen as a necessary large investment that is justifiable. No one wants to be left out, and many perceive opportunities to gain a place in what is essentially a new competitive environment from which no one is yet excluded and in which no one is yet the winner.

None of the national efforts would have been as effective, nor will they be so in the future, without the investment of hundreds of millions of dollars by the private companies involved. These corporations, in turn, can invest more because the government programs both help to lower the risks involved and leverage and network resources that the companies cannot influence by themselves. The rewards, however, are particularly large in light of the size and impact of the potential global market and the potential gains in environmental preservation and energy efficiency.

The global context raises the question of what type of international collaboration is absolutely necessary, and what type of cooperation it makes scientific and economic sense to pursue regionally and globally. It also raises the question of whether a national government can or should help its companies become world leaders in all areas, or focus its efforts on select component and technology fields.

5.1.6.3.3. The Remaining Hurdles

Significant technical and infrastructure barriers remain. Even if those barriers fall, it will be many more years before the world's automotive fleets can turn over and accommodate substantial numbers of fuel cell vehicles. There is not yet a hydrogen infrastructure, even in the most industrialized nations, to support even a moderate number of fuel cell vehicles. Such an infrastructure might be developed sooner in small countries. But everywhere else, it will take many years to develop and be cost-effective.

The biggest hurdle, however, is the long-term sustainability of an extremely costly public-private effort over the 15 to 20 years minimum it will take to build a

commercially viable industry and the infrastructure to support it. Is the public policy interest high enough to sustain investment and provide cost-lowering financial offsets in order to make fuel cell vehicles and a hydrogen infrastructure competitive with advanced internal combustion vehicles and petroleum fuels in terms of cost and performance? Can public interest be built with other types of energy-efficient, environmentally friendly vehicles that ultimately will make fuel cell vehicles easier to accept? What economic and technological dislocations will occur along the way, and what costs will be needed to ameliorate them? What is certain is that the race to produce fuel cell vehicles is taking place in a global industry with a wide variety of players. It will cause continued shake-ups in the vehicle, fuel cell, and supplier industries. The race will have long-term global technological and economic effects on energy use and mobility. How long it will take, and whether it is a marathon or a series of sprints, is not yet certain.

5.2. Comparison of two Production Methods

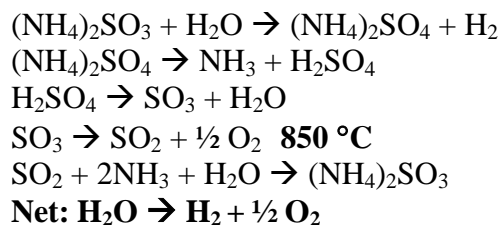
5.2.1. Hydrogen from Non-Fossil Fuel Based Sources

5.2.1.1. Objective

This section will look at hydrogen production not based on fossil fuels, specifically focusing on the design of hydrogen production using the sulfur/iodine thermochemical cycle powered by nuclear energy.

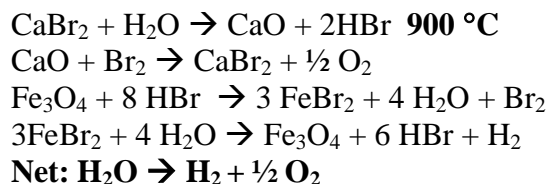
5.2.1.2. Introduction

There are a number of methods to produce hydrogen that do not require the use of fossil fuels. The simplest is electrolysis powered by non-fossil fuel sources of electricity. (See the Hydrogen Economics section of this report.) Hydrogen can also be produced directly from solar energy. A system recently proposed by T-Raissi involves the photochemical reaction of ammonia sulfite to produce ammonia sulfate and water. The complete reaction sequence is:



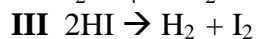
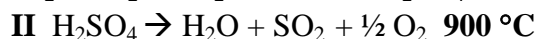
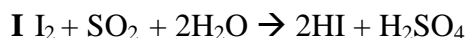
We haven't seen any follow up work published on this route.

Currently the most promising route for non-fossil-fuel based production of hydrogen are from thermochemical cycles, where the heat is provided by a nuclear reactor. The system receiving the most attention now is the UT-3 cycle of Kameyama and Yoshida. The reactions are:



The main focus of research is on solids handling and separations, and this process has limited value for design study by those not directly involved in the research.

The most efficient demonstrated (lab scale) production of hydrogen not involving fossil fuels is the sulfur/iodine cycle developed by General Atomics. The reactions are:



Unlike the UT-3 cycle, the sulfur/iodine cycle should be an all fluid process, with minimal side reactions. It also generates hydrogen at high pressure, so no subsequent hydrogen compression is required. This process has a demonstrated efficiency of approximately 50%, and it has been studied both focusing on the nuclear heat source and the process chemistry. Aspentech and General Atomics reported the results of a simulation emphasizing the good match between the results of Aspentech's Electnrtl property set and experiment. A second publication by the same group showed detailed flow sheets and material balances (almost 100 streams) and estimated the overall capital and operating cost without listing the details.

We have decided to use Aspentech/General Atomics results as a basis for our flowsheet, and used Aspen and the Electnrtl property set to simulate the process. A number of simplifying changes were made to the process; these will be discussed. We will also present sizing and economic details and compare our overall estimates of capital and operating cost with those of Aspentech/General Atomics. Our design will not provide the level of detail required for designing a plant (P&ID needed), but should serve as a useful way of communicating the key technical and economic issues associated with hydrogen production from the sulfur/iodine process.

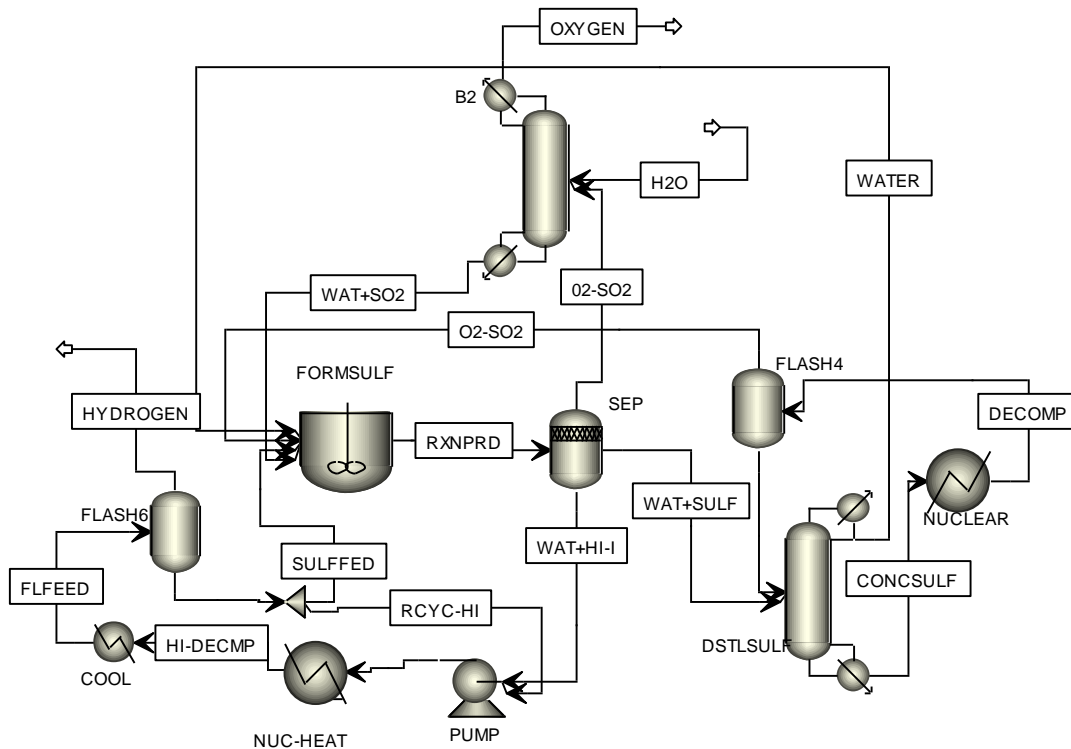
5.2.1.3. *Process Overview and Design Basis*

There are three sections to the process. The first section involves the formation of sulfuric acid and hydrogen iodide ($\text{I}_2 + \text{SO}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{HI} + \text{H}_2\text{SO}_4$), followed by the separation of HI from H_2SO_4 . The key to this step is that in the presence of excess iodine the $\text{I}_2/\text{HI}/\text{water}$ forms a separate phase from sulfuric acid/water. The second section involves the concentration of sulfuric acid by water distillation followed by high temperature (900 C) decomposition ($\text{H}_2\text{SO}_4 \rightarrow \text{H}_2\text{O} + \text{SO}_2 + \frac{1}{2} \text{O}_2$). The third section involves the decomposition HI ($2\text{HI} \rightarrow \text{H}_2 + \text{I}_2$). A key to this step is that the the iodine does not need to be separated from the HI before the decomposition. Also the hydrogen is produced at 300 psig without requiring compression. Overall the process is very energy intensive, so the design includes a nuclear power plant supplying the heat and electrical energy to the process.

We had hoped to use the production rate in the hydrogen from natural gas section of this report as the design basis for the sulfur iodine process. Unfortunately this leads to unrealistically large equipment sizing, as does the sizing used by AspenTech. (The AspenTech publication states that at least 5 separate trains would be required) We therefore used the largest practical equipment size as a design basis. For the sulfur iodine cycle the 1st and 3rd sections require the largest equipment. This is because the large excess of iodine and water necessary for the section one reaction ($I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4$) and separation is fed into the HI decomposition section, requiring several large reactors and a large settler in section I and a large pump and very large heat exchangers in section III. We therefore have chosen 2000 lb/h of hydrogen (7300 tons/y of hydrogen) as a production. The resulting HI/I/water flow rates are up to 16,000,000 lb/h.

The fixed cost estimate for the process was determined by using a factored estimate from the estimated purchased cost for most expensive pieces of equipment. The operating expenses primarily are the energy requirements for the process. We will not estimate the cost of the nuclear power plant, but instead charge energy requirements as the major operating cost.

5.2.1.4. Simplified Process Flow Diagram



Detailed Process Flow Diagrams and Material Balances for each stream can be found in the Appendix.

5.2.1.4.1. Process Description

Reaction I section ($I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4$)

The flow rates for this section are quite large due to the large excess of iodine and water required to effect the sulfuric acid/HI separation. The reaction was modeled as a conversion block using the AspenTech conversion. The reactor cost estimate was based on 5 x 10,000 gallon alloy-20 CSTR's. This requires a rapid reaction, which is the basis for AspenTech's estimates. The decant step is difficult to model, so we used AspenTech's result. Cost and sizing was based on a 260,000 gal horizontal pressure vessel, affording a 20 min residence time. Rather than using a distillation column as shown in the PFD, we used two flash drums with a chiller in between. The first flash drum is alloy 20; the second is carbon steel.

Reaction II section ($H_2SO_4 \rightarrow H_2O + SO_2 + \frac{1}{2} O_2$)

The flow rates in this block are considerably lower than in section I, as the decanter in section one sends most of the material into section III. As a result, the equipment sizing in section II is more reasonable. The most challenging part of this section to simulate is the sulfuric acid distillation. Sulfuric acid/water mixtures are not concentrated industrially by distillation, but the alternative for this cycle would be a very expensive water removal using polyphosphoric acid. We have therefore followed the published simulation in spirit, while greatly simplifying the 9 flashes in the published flowsheet into one flash and one distillation. The distillation was modeled rigorously (Radfrac block), and required 4 theoretical stages. The column diameter was determined both using Aspen and by hand using the Eckert correlation; this led to similar results and the hand calculation was chosen. Alloy 20 was chosen for the concentrated sulfuric acid service.

The sulfuric acid decomposition requires extremely high temperatures but short residence times, so only a heat exchanger is required for cost estimations. The reaction was modeled with a conversion block using the AspenTech result. The heat is supplied by a nuclear heat source. The extreme conditions of temperature and corrosivity require an educated guess for the materials of construction (lab tests used quartz). We chose alloy G for the heat exchanger as being highly resistant to sulfuric acid corrosion.

Reaction III section ($2HI \rightarrow H_2 + I_2$)

This section poses significant modeling and process challenges: A) water iodine forms an azeotropic mixture, B) iodine can precipitate out below 114 C, C) the water/HI/I₂ system exhibits a complex liquid/liquid equilibrium, and D) the huge flow rates require very large equipment. The last point required that this section determine the production design basis for the entire plant. AspenTech found that the Electnrtl parameter set reasonable approximated experimental data, but they could not get the HI reactive distillation to converge after considerable effort. We followed their lead and instead modeled this step as a low conversion recycle process with flash of the hydrogen at 300 psi. The HI decomposition is rapid, so heat exchangers are sufficient to provide the residence time. The large flow rates require huge heat

exchangers –one 35,000 sq ft and three 62,000 sq ft. The high flow rates also require considerable heat from the nuclear source (400 MW), much larger in fact than required for the sulfuric acid decomp (12 MW) even though the maximum temperature (570 F) is much lower than for the sulfuric acid decomp (1650 F). We chose monel for the heat exchangers as HI is expected to be moderately corrosive at the high temperatures involved. Sizing the heat exchangers was based on the method suggested in the 494 textbook. Cost estimates for the exchanger were based on averaging results from the 494 text correlation and results from the Aspen Icarus cost estimator.

5.2.1.4.2. Major Equipment List and Sizing

Cost estimates were made for the following pieces of equipment: continuous stirred tank reactors (CSTR), flash drums, multiple heat exchangers, a tank for liquid/liquid separation, a distillation column and a vacuum pump (steam ejector) and a centrifugal pump. Details can be found in the appendix. Estimates for the most expensive pieces were made both using the 494 text and either the Aspen Icarus Cost Estimating Program or a cost estimation website. The most expensive pieces of equipment were: A) the four CSTR's, with a total purchase cost \$17 m (million), B) the liquid/liquid separator at \$6 m, 3) the heat exchangers from the HI decomp section at a total of \$ 9.3 m, and 4) 5 storage cylinders for hydrogen at a total cost of \$2 m. All of these pieces of equipment are quite large due to the previously mentioned large excess of water and iodine, and all require expensive materials of construction.

5.2.1.4.3. Energy and Utilities

The process is quite energy intensive and requires a nearby nuclear reactor for heat and power. We divided the energy usage into heat requirements and electrical requirements. The main heat consumers of for the process are the sulfuric acid distillation column reboiler, requiring 55,000 KW of heat, and one of the heat exchangers from the HI section, requiring 410,000 KW of heat. The main electrical users are refrigeration before the hydrogen flash for section III and the centrifugal pump for section III. Further details can be found in the Appendix.

5.2.1.5. *Fixed Capital, Operation Cost, and Overall Economics*

The fixed capital estimate was made by sizing and costing the most expensive pieces of equipment, then applying a factor of 3 yield the installed cost. To this was added a percentage for some overhead expenses (see Capital Cost Estimate table on next page) and the initial start up cost for the HI and I₂. Together this leads to a fixed capital estimate of \$141 m (million).

The operating cost is primarily the cost of energy (see operating cost estimate on next page). Heat was charged at \$400/KW-y (about 4 cts/KW-h) and electrical was charged at \$1000/KW-y. These numbers appear to be the ones used by Apentech (the data not was not presented clearly) for energy for a neighboring nuclear power plant. The numbers seem plausible, so we decided to use them. We estimated an efficiency of 90% for the heat and 40% for the electrical. Together, this leads to an exceedingly large total operating cost of \$317 m/y. This value makes some sense when taking into account the 8000 lb of water/HI/I₂ that have to be processed (and vaporized) for every 1 lb of hydrogen produced.

The Project Economic Evaluation Spreadsheet shows that a sales price of \$ 48/kg of hydrogen (= \$350 m/7.3 kT) is required to recoup the cost of capital at 9% rate of return for this project. About 90% of this cost is needed to cover the energy cost of the process. If the more realistic energy price is used. This compares to current hydrogen production cost of \$1-3/kg. See next section on comparison to published estimates.

CAPITAL COST ESTIMATE : SULFUR-IODINE BASED HYDROGEN PRODUCTION

Equipment Description			Num Items	Capex US\$x1000	
Name	Description	Matl Of Const		Equipment	Installed
I2	Storage Tank Fixed Roof	alloy	1	600	957
aq HI	Storage Tank Fixed Roof	alloy	1	600	957
H ₂ stor	Pressure Vessel	SS	5	1,500	2,382
Sulfuric stor	Storage Tank Fixed Roof	alloy 20	1	210	335
Heat Ex	Heat Exch S&T	Monel	1	850	1,341
Heat Ex	Heat Exch S&T	Monel	3	8,400	13,251
Vac Pump	Steam ejector	CS	1	120	225
Pump	Pump Centifugal	SS	1	300	476
Dist Colmn	Pressure Vessel	alloy G	1	240	422
Colmn Packng	Column Int Pall Rings	alloy G	1	160	205
Decant	Pressure Vessel, horiz	alloy 20	1	6,000	10,557
Reactor	CSTR	alloy 20	4	17,000	29,912
Subtotal				61,020	61,020
Offsites Facilities %				0	-
Sub Total Including Offsites					61,020
Freight & Import Duties (4%)				0	-
Contractor Home Office (15 %)				15	9,153
Contractor Site Supervision (10%)				10	6,102
Sub Total Including Contractor & Duties					76,275
Owners (10 %)				10	7,627
Chemicals Startup					32,000
Total Including Owners and Catalyst, Chemical & Royalties					115,902
Contingency (15%)				15	25,763
Grand Total Including Contingency				US\$x1000	141,666

Operating Cost Estimate

Operating costs						
	Chemicals	Energy - Heat	Energy-electrical	Labor	Other	Total
cost (\$K/y)	\$3,000	\$210,000	\$100,000	\$2,240	\$1,760	\$317,000
notes	3% of startup	at \$400/KW-y, 90% effic.	at 1000/KW-y, avg 40% effic	8 operators x 4 shifts x \$70k/y	3% of tot. e.g. water, waste treatment, overhead, maintnce	

Project Economic Evaluation									
Non-Fossil Fuel Based Hydrogen Production									
November 19, 2004									
	2005	2006	2007	2008	2009	2010	2011	2034	2035
Capital Investment (\$m)	142								
Expenses (\$m)	25	150	275	317	317	317	317	317	317
Savings/Revenues (\$m)		100	242	320	350	350	350	350	350
Depreciation (\$m)		28.40	45.44	27.26	16.36	16.36	8.18	0.00	0.00
Taxable Income (\$m)	-25.00	-78.40	-78.44	-24.26	16.64	16.64	24.82	33.00	33.00
Taxes (\$m)	-9.00	-28.22	-28.24	-8.74	5.99	5.99	8.94	11.88	11.88
Net Cash Flows (\$m)	-158.00	-21.78	-4.76	11.74	27.01	27.01	24.06	21.12	21.12
Cumulative NPV (\$m)	-143.77	-161.95	-165.60	-157.35	-139.94	-123.97	-110.91	-1.13	0.32
NPV9 (\$m)	\$0.32								
IRR	9.0%								
Capital Efficiency	0.2%								
Discounted Payback	N/A								
Tax rate	36%								
Withholding Tax (WHT) rate	5%								
Discount rate	9%								
Discounting basis year	2005								
Cash Flow Units	\$m								
Depr. schedule	20.0%	32.0%	19.2%	11.5%	11.5%	5.8%			

5.2.1.5.1. Comparison with Published Estimates

Hydrogen Production costs from commercial plants are on the order of \$1-3/kg. (See Hydrogen Economics section of this report). For the sulfur-iodine process, Aspentech estimated \$500 m capital investment for a 240 kT/y plant (not including contingency and initial working capital). Using a 0.6 factor scale down, this suggests \$61 m for a 7.3 kT/y plant compared to our estimate of \$76 m – a surprising level of agreement.

Their estimate for the initial chemical inventory is \$ 115 m. Using a 0.8 factor, this suggest a number of only \$7m compared to our value of \$ 32 m. They must be using a much smaller reactor and decanter, as these are the main wide spots in the line in our process.

Their operating cost estimate is much lower than ours – with an estimate of about \$1/kg compared to our value of about \$43/kg. A number of factors could be used to explain a difference of a factor of 2 - 3, but the only one that could explain such a large discrepancy is their reactive distillation. They were not able to get their reactive distillation to converge for the flow sheet, but they appeared to use it for the economic evaluation. The HI reactive distillation is somewhat of a black box on their flowsheet, but somehow for every 126 moles of material that go into the still, less than 3 moles of material is converted to a vapor (at 590 F). For our partial decomposition/Flash/recycle system, about 90% of the material is converted to vapor at the same temperature and pressure.

5.2.1.5.2. Conclusions

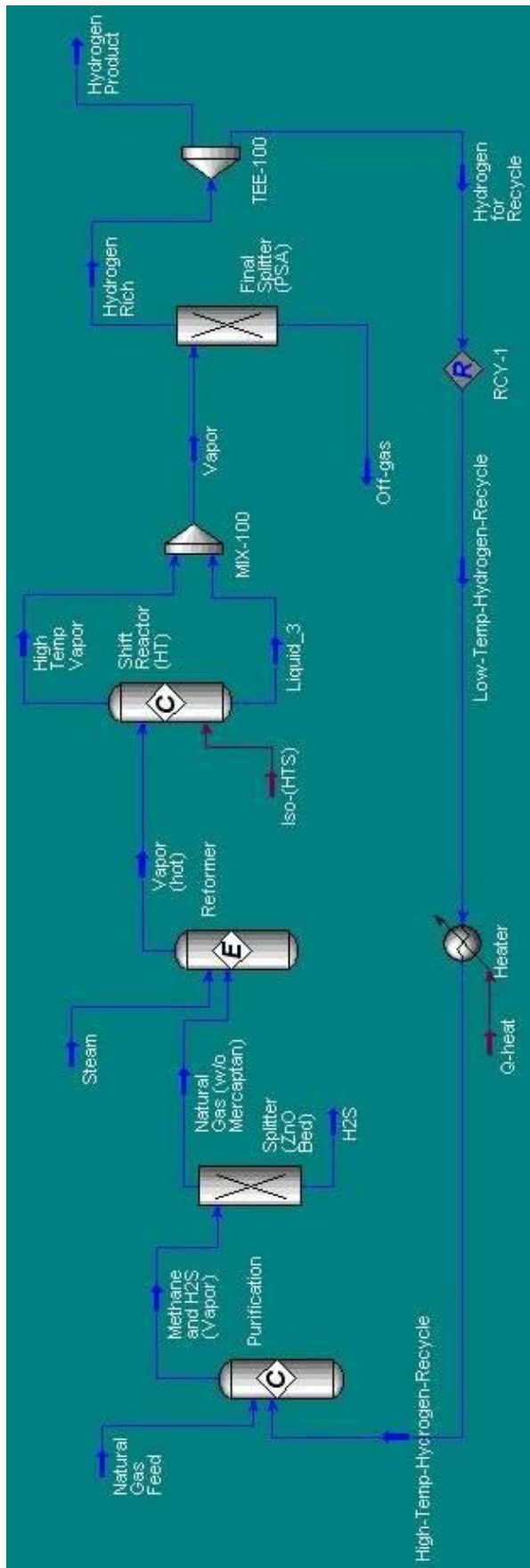
We developed a process for hydrogen production not requiring fossil fuels based on the sulfur iodine cycle. A large excess of iodine and water is required; this makes the process very demanding of energy from a nearby nuclear powered plant. Economic analysis leads to a hydrogen production cost of \$48/kg. This compares to current hydrogen production costs of \$1-3/kg. The cost of production for the process is dominated by the energy requirements.

Hydrogen Production through the sulfur iodine cycle is a good problem for teaching process design principles and methods, but it appears unrealistic for commercial hydrogen production.

5.2.2. Hydrogen from Natural Gas

Hydrogen is very useful as a fuel, as it is used in many modern day processes: fuel cell operation, hybrid vehicle operation, etc. In the future, as the supply of fossil fuels diminishes beyond the point of being affordable for the world's everyday needs, an alternative source will need to be chosen. It is believed that hydrogen may be the next fuel of choice. Currently, hydrogen is produced commercially from methane in natural gas for many of the processes described above, and an issue is arising concerning the increased demand for hydrogen. Because of the current demand and the predicted demands of the future, we have designed a hydrogen production plant from the methane in natural gas using HYSYS as the simulation software. Please see Figure 16 for the design. Upon designing a working simulation, we adjusted the hydrogen production rate to calculate the necessary inlet flows of natural gas and steam. By using the flow rates through the reactors, we were able to size the reactors, and eventually determine their costs. Finally, we determined the cost of the catalysts to fill them, as well as the feed streams and utilities. In order to determine the annual cost to build and operate the plant, we looked at appropriate economics to amortize the price.

Figure 16: Hydrogen Production Plant



5.2.2.1. Simulation Design

Natural gas is comprised of several components, including methane, nitrogen, carbon dioxide, oxygen, trace amounts of hydrogen and mercaptan, and several other low weight hydrocarbons. Typical analysis shows that methane accounts for approximately 95% by mole of natural gas. Mercaptan is an additive sulfur agent, used to give natural gas a distinct odor. Without mercaptan, exposure to natural gas can cause serious damage, or death, because methane is quite toxic.

Production of hydrogen from natural gas requires three reactions (one of which occurs twice) and two separations:

$CH_4S_{(g)} + H_{2(g)} \rightarrow CH_{4(g)} + H_2S_{(g)}$	Reaction 0: Purification
$CH_{4(g)} + H_2S_{(g)} \rightarrow (CH_{4(g)}) + (H_2S_{(g)})$	Separation 1: Component separation
$CH_{4(g)} + H_2O_{(g)} \Leftrightarrow CO_{(g)} + 3H_{2(g)}$	Reaction 1: Steam/Methane reformation
$CO_{(g)} + H_2O_{(g)} \rightarrow CO_{2(g)} + H_{2(g)}$	Reaction 2 (& 3): Water-gas shift
$CO_{2(g)} + H_{2(g)} \rightarrow (H_{2(g)}) + off - gas$	Separation 2: Product separation

Reaction 0 is a purification reaction, which converts any sulfur compounds in the natural gas to hydrogen sulfide. If left in the system, sulfur compounds can poison the catalysts used for successive reactions. Mercaptan is the primary sulfur compound in natural gas. Because the reforming reaction is equilibrium limited and favored at high temperatures and low pressures, we chose to operate the purification reaction at a high temperature and a low pressure: $T = 800^\circ\text{C}$ and $P = 250 \text{ kPa}$. Also, a 100% conversion has been assumed in the simulation, because we don't want any unreacted mercaptan. Separation 1 separates hydrogen sulfide from the remaining natural gas. The literature suggests that a zinc oxide bed be used for this separation. For the simulation, we have decided upon a pressure drop of 100 kPa within the bed: the pressure of the outlet vapor stream is [200 kPa] 50 kPa less than that of the feed stream; and the pressure of the outlet liquid stream is [300 kPa] 50 kPa more than that of the feed stream.

The reforming reaction, Reaction 1, is an endothermic process characterized by an increase in the total number of moles. Because of this, high temperatures and low pressures are necessary for a high equilibrium conversion. For the natural gas, the literature suggests an inlet temperature in the range of $788\text{-}880^\circ\text{C}$ and an inlet pressure in the range of 1.4-3.8 MPa. These inlet parameters were chosen as $T = 800^\circ\text{C}$ and $P = 200 \text{ kPa}$. In order to achieve a high conversion in an equilibrium reaction, Le Châtelier's principle suggests that one reactant be added in excess of the other reactant. In addition to Le Châtelier's principle, the addition of one reactant

to completely consume the other reactant also protects the catalyst. Typically, the cheaper reactant is added in excess, and in this case, the cheaper reactant is steam. For this reaction, the excess steam will ensure complete conversion of the methane. This will protect the catalyst and reduce the chance for carbon deposits. The literature suggests steam is added in a ratio of 2.5 to 4:1 at a pressure of 2.6 MPa. So the inlet steam parameters were chosen as $P = 2600 \text{ kPa}$, and $\dot{n} = 3703 \text{ kgmol/h}$, which is four times the flow rate of natural gas that enters the reactor. The inlet temperature of steam was also chosen, $T = 1700^\circ\text{C}$.

As already noted, the water-gas shift reaction occurs twice: once at a high temperature, and once at a lower temperature. The high-temperature shift reaction is chosen to be at $T = 350^\circ\text{C}$; the low-temperature shift reaction is chosen to be at $T = 200^\circ\text{C}$. The pressure of these reactors is predetermined from the previous reforming reaction: $P = 200 \text{ kPa}$. An overall conversion of 92% based on CO is desired, which requires a conversion of 72% in each shift reactor. The major product of the shift reactors is hydrogen, which is the desired product of the entire plant. At this point, hydrogen must be separated from the remaining compounds in the plant.

Separation 2 separates the hydrogen from the remaining compounds in the plant, which are called off-gases. Typically, a pressure swing adsorption (PSA) unit is used for this operation. A simple PSA unit consists of several adsorption columns connected in parallel. Each column contains a bed of adsorbent material and takes in a portion of the feed gas at a given pressure. The adsorbent material depends on the impurities of the feed gas, i.e.: the gases that need to be removed from the desired product, but zeolites, alumina gel, and activated carbon are commonly used. Once inside the column, the feed gas travels upward through the adsorbent material, where it is separated from the impurities. Once the product has left the column, the pressure is reduced and the impurities leave the column through the bottom. The column is repressurized for the next batch of incoming feed gas. A more complicated PSA unit, or one found in industry, will have each of the columns that are connected in parallel, connected to additional columns in series. The 'swing' in this unit is the pressure fluctuations.

5.2.2.2. *Simulation Size: Sizing the main Reactors*

To size the purification reactor, it was necessary to make an assumption about the resonance time. We assumed it would take 120s, because it is a gas phase reaction taking place at an increased temperature and pressure. Using the required volumetric flow rate of $46.113 \text{ m}^3/\text{h}$, an area was assumed. Initially, a 2-meter diameter and a 6-meter diameter reaction vessel were calculated, however they yielded extreme results. A smaller value of 1-meter was tried next, which yielded a superficial velocity of 0.0163 m/s . From this and the resonance time, the length of the reactor was found to be approximately 2 meters.

To size the methane steam reforming reactor and the water-gas shift reactors, the rate laws of each reaction were investigated. The rate laws used were proposed in accordance with Xu and Froment:

$$r_1 = \frac{\frac{k_1}{p_{H_2}^{2.5}} \left(p_{CH_4} p_{H_2O} - \frac{p_{H_2}^3 p_{CO}}{K_1} \right)}{(DEN)^2} \quad (\text{Eqn 7})$$

$$r_2 = \frac{\frac{k_2}{p_{H_2}} \left(p_{CO} p_{H_2O} - \frac{p_{H_2} p_{CO_2}}{K_2} \right)}{(DEN)^2} \quad (\text{Eqn 8})$$

Where:

- K_i = Equilibrium constant of the i th Reaction
- k_i = Specific Reaction Rate Constant of the i th Reaction
- p_J^m = Partial Pressure of Species J raised to the m^{th} Power

For each rate law, DEN is an expression involving partial pressures and adsorption coefficients:

$$DEN = 1 + K_{CO} p_{CO} + K_{H_2} p_{H_2} + K_{CH_4} p_{CH_4} + K_{H_2O} p_{H_2O} / p_{H_2} \quad (\text{Eqn 9})$$

Where:

- K_J = Adsorption Coefficient of Species J
- p_J^m = Partial Pressure of Species J raised to the m^{th} power

To determine the amount of catalyst needed for each reaction, the following equation was used relating the flow rate of the basis component to the rate law, assuming no pressure drop within the reactor:

$$W = \int_{F_{A0}}^{F_A'} \frac{F_A'}{r_i} \quad (\text{Eqn 10})$$

Where:

- W = Weight of the Catalyst
- F_A' = Flow rate of the basis Component
- r_i = Rate Law of the i th Reaction

Once the weight of the catalyst is known, if it is divided by the density, the volume of catalyst is determined. From the volume of the catalyst, the volume of the reactor is determined by dividing by the one minus the void fraction. These two formulas are as follows:

$$v = \frac{W}{\rho} \quad (\text{Eqn 11})$$

$$V = \frac{v}{1 - \varepsilon} \quad (\text{Eqn 12})$$

Where:

- v = Volume of the Catalyst
- ρ = Density of the Catalyst
- V = Volume of the Reactor
- ε = Void Fraction in the Reactor

The rate laws were proposed based on experiments done with a nickel-based catalyst and a void fraction of 0.528. The density of the catalyst is estimated to be 1,050 kg/m³, based off of commercially available nickel catalysts from the Johnson Matthey Catalysts company.

As a result, approximately 44,000 kg of catalyst is needed for the reforming reaction, resulting in a reactor volume of approximately 88 m³. In order to build a plant within physical constraints, it has been determined to only use one water-gas shift reactor, the high-temperature reactor. As technology is progressing, this has actually been discovered as a new trend. The amount of catalyst needed for the high-temperature shift reactor is approximately 588,000 kg, resulting in a reactor volume of nearly 1,200 m³. If the diameter of each reactor is 2 m, the lengths are 28 m and 378 m, respectively. If the diameter of each reactor is 2.5 m, the lengths are 18 m and 242 m, respectively. If a plant cannot house a reactor as long as these proposed for the water-gas shift reaction, smaller reactors can be connected in series, as long as the total length is conserved. This is an important trait of packed-bed reactors.

5.2.2.3. Simulation Cost

From the volumetric flow rate of natural gas entering the process, and the price of natural gas per volume, the annual cost of natural gas was found:

$$Cost_{nat-gas} = \dot{V}\delta_{ng} \quad (\text{Eqn 13})$$

Where:

- \dot{V} = Volumetric Flow rate of the Natural Gas
- δ_{ng} = Cost of Natural Gas per 1000 cubic feet (\$6.28/1000 ft³)

It was determined that natural gas would cost approximately \$9.22/h, and if the plant was operated for 8500 hours per year, the annual cost would be approximately \$78,000.

Steam needs to be provided to the reformer at a rate of 68,000 kg/h, and at a cost of \$0.006 kg⁻¹, an equation almost identical to Equation 7 can be developed, which will result in an annual cost of \$3.5 million.

A total of 632,000 kg of catalyst is needed (with a density of 1,050 kg/m³), and at a price of \$650/ft³, a similar equation can be derived to determine the cost of the catalyst:

$$Cost_{catalyst} = m\delta_{cat} \quad (\text{Eqn 14})$$

Where:

- m = Mass of Catalyst needed
- δ_{cat} = Cost of Catalyst per cubic feet

It was determined that the catalyst would cost approximately \$14 million, and it would have a life span of roughly five years.

In costing the purification, methane reformation, and water-gas shift reactors, the methods of Mulet, Corripio, and Evans was used, which is based on reactor weight and two 2:1 elliptical heads. Since all our reactors are assumed to be horizontal reactors, the following equations were used:

$$C_p = F_M C_v + C_{PL} \quad (\text{Eqn 15})$$

$$C_v = \exp \left\{ 8.717 - 0.2330[\ln(W)] + 0.04333[\ln(W)]^2 \right\} \quad (\text{Eqn 16})$$

$$C_{PL} = 1,580(D_i)^{0.20294} \quad (\text{Eqn 17})$$

$$W = \pi(D_i + t_s)(L + 0.8D_i)t_s\rho \quad (\text{Eqn 18})$$

$$t_s = t_p + t_c \quad (\text{Eqn 19})$$

$$t_p = \frac{P_d D_i}{2SE - 12.P_d} \quad (\text{Eqn 20})$$

$$P_d = \exp \left\{ 0.60608 + 0.91615[\ln(P_0)] + 0.0015655[\ln(P_0)]^2 \right\} \quad (\text{Eqn 21})$$

Where:

- C_P = Purchase Cost, in dollars
- F_M = Correction Factor, depending on the material the reactor is made of
- C_V = Empty Vessel Cost, in dollars
- C_{PL} = Added Cost for Platforms, Ladders, etc..., in dollars
- W = Weight of the empty Vessel, in pounds
- D_i = Inner Diameter of the Vessel, in feet
- t_s = Shell Thickness, in feet
- ρ = Density of the Material, in pounds per cubic feet
- t_p = Wall Thickness, in feet
- t_c = Corrosion Allowance, equal to 1/8 inch, in feet
- S = Maximum Allowable Stress of the reactor, in pounds per square inch (psi)
- E = Weld efficiency, equal to 0.85 for wall thickness less than 1.25 in
- P_d = Design Pressure, in psig
- P_0 = Operating Pressure of the reactor

The cost of the purification reactor was determined to be approximately \$14,500. A cost analysis of the reformer and the water-gas shift reactor was done for each vessel at each diameter discussed previously. With a diameter of 2-meters, the reformer would cost approximately \$71,000, whereas it would cost approximately \$69,000 with a diameter of 2.5-meters. With such a small difference, the reactor should be chosen based on plant limitations. With a diameter of 2-meters, the water-gas shift reactor would cost approximately \$526,000, whereas it would cost approximately \$480,000 with a diameter of 2.5-meters. Clearly, the water-gas shift reactor with the larger diameter should be chosen.

At this point, costing analysis techniques have been used to determine the cost of the natural gas feed; the steam feed to the reformer; the nickel-based catalyst in the reformer and the shift reactor; and the reactor vessels. Choosing the most expensive estimates for all the reactors, and the price of the catalyst, the annualized cost of the plant can be determined:

$$C_A = i_m(C_{TCI}) + C \quad (\text{Eqn 22})$$

Where:

- C_A = Annualized Cost, in dollars
- i_m = Rate of Return
- C_{TCI} = Total Capital Cost, in dollars
- C = Cost of Utilities, in dollars

The capital investment of this hydrogen production plant is approximately \$14.6 million, and the annual cost of utilities is approximately \$3.6 million. The cost of the zinc oxide bed; the pressure swing adsorber; the pumps (compressors) and heaters necessary to raise temperatures and pressures; and the heat exchanger that could be used for heat transfer between the vapor leaving the reformer and the hydrogen recycle stream have not been investigated. Also, nothing has been done with the off-gas to make sure that toxins are not being spewed into the environment. With all that has been costed and not costed, we will assume a price twice that of the costed portion, at an interest rate of 10%. This results in a total annual cost of approximately \$10 million. At a production rate of nearly 5,800 kg/h (49 million kg/year), hydrogen must be sold at approximately \$0.21 per kg, in order to break even. Currently, hydrogen is sold at a much higher price, leaving room for quite a profit. Considering that we assumed the uncosted portion of the plant to be nearly the same as the costed portion, if the uncosted portion is much more expensive, hydrogen can still be produced at a price low enough that its mark-up will provide a remarkable profit.

Note: This hydrogen production plant design relies on numerous sources. It is often unwise to cross-reference sources when trying to replicate a design for any process, which is why the minimum cost of hydrogen to the consumer may seem low. Had fewer sources been referenced, the predicted cost of hydrogen per kilogram using HYSYS would certainly be different.

6. Conclusion

In striving to design and produce a hybrid fuel cell/electric vehicle, each of the teams was forced to overcome unexpected challenges. For the hybrid team, this meant multiple reevaluations of the team structure as well as the overall goals. For the battery team, these challenges included safety circuits that sometimes seemed to be more hazardous than safe. It also involved tireless hours in the lab working to solder wires, sometimes only millimeters apart. For the vehicle design team, obstacles included building a more reliable, lighter towing system for the fuel cell. Mounting a seat to a rather unfriendly attachment was tackled as well. For the knowledge team, it meant gathering dozens of documents and organizing them in such a manner that future teams will find them useful. Finally, the website design team had to constantly adapt to changes made, while still keeping the entire group up to date.

In addition to physical vehicle applications, several elements involved in conversion to a hydrogen economy were studied. First, the safety of using hydrogen was compared to that of gasoline. While there is considerable public concern about using hydrogen, the evidence is ambiguous as to whether hydrogen is more of a safety risk than gasoline. Second, the economics of hydrogen production, storage, and delivery were reviewed. Design of cost effective hydrogen storage devices and construction of appropriate delivery systems are the major obstacles to implementation of a hydrogen economy. Third, two different detailed designs were performed for hydrogen production. One design looked at a plant that produces hydrogen from natural gas using existing steam reforming technology based on known kinetics. The price estimate was toward the low end of published values. A second more futuristic and speculative design was performed for hydrogen production using the sulfur/iodine thermo chemical cycle powered by a nearby nuclear power plant. The production cost for this system was found to be more than an order of magnitude higher than for the natural gas based plant.

As a team we were able to work together to accomplish many of these seemingly impossible hurdles. Although not all of our initial objectives were completed, our team came a long way. Anyone from IPRO 304 could tell you the importance of teamwork and group communication. They would also be able to elaborate on the importance of facing change with new ideas and shifting ones paradigm to adapt. All of these and more were lessons learned throughout the semester. Overall, our IPRO was a great success!

7. Future Recommendations

While the extended drive did not happen, there is a very high potential of success in the near future. The last of the setbacks were in getting all of the electrical connections completed and receiving the DC/DC converters and battery chargers.

There were three stated needs from the last IRPO: 1.) finding a more effective method for hooking the batteries to the vehicle, 2.) the distance between the vehicle and the trailer is too small and needs to be extended to allow for smaller turning radiuses. Also, the attachment between the trailer and the wheelchair needs to be improved to prevent bending of the pins, and 3.) a charger circuit needs to be perfected in order to implement the fuel cell as a battery charger. These three needs were addressed and completed in this IPRO.

What remains, still, is to fully “hybridize” the vehicle. Using the fuel cell to power the vehicle under constant conditions and using the batteries to provide power when variable power is needed. This will further explore the feasibility of using the Li ion batteries with the passive cooling system in hybrid electric vehicle applications.

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- The price of the catalyst and its life expectancy came from a phone conversation with Steve Zeglin, from the Johnson Matthey Catalysts company on 11/23/04.

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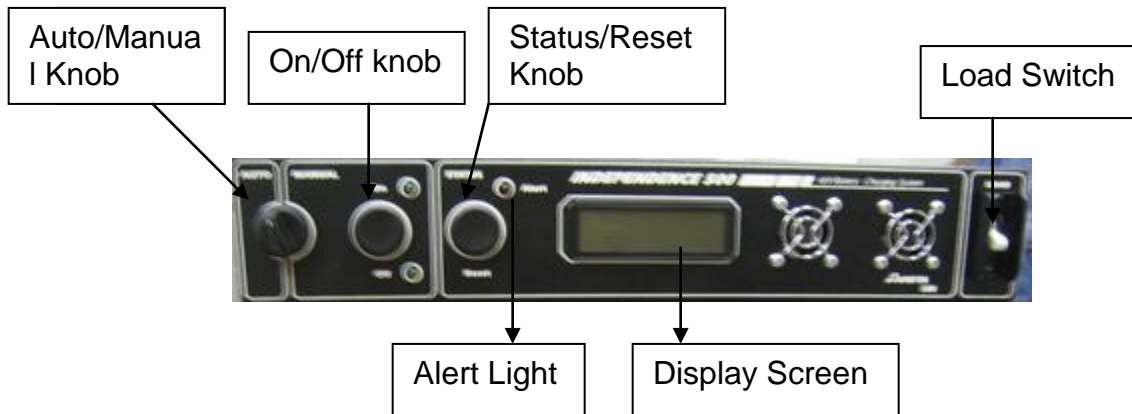
- Microsun Technologies
- ReliOne Inc.
- UOP
- All Cell Technologies

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10. Appendix

10.1. Operation Manual of the Fuel Cell

Figure 17: Fuel Cell Top Panel.



Starting up the Avista Fuel Cell

- 1) Before starting up the fuel cell, flood the whole system with hydrogen by connecting the hydrogen to the fuel cell and turning the pressure up to a pressure between 40-180 psi for about fifteen minutes. This will enable all the modules to get flooded with hydrogen and a continuous flow of hydrogen is established. Note that if the modules have not yet been filled with enough hydrogen, it may cause the display to say “# of modules offline”.
- 2) **DO NOT OPERATE THE FUEL CELL INDOORS WITHOUT IT BEING UNDER A VENTILATED HUB OF SOME KIND.** It would be best to use it only outdoors or in a very good ventilated room. This is because while flooding the fuel cell for fifteen minutes, hydrogen is continuously pumped into the room and if a spark for any reason is created everything could literally go boom.
- 3) To start up, the fuel cell needs about 36-50V of potential difference to give it a kick start. This start requires almost no current. To do this attach the batteries to the fuel cell and remember this is done after the hydrogen had been flowing through the system for fifteen minutes.
- 4) Switch the load switch into the on position and then press the start button. If everything works correctly the display should show a progress bar that gradually increases until it hits roughly 50-54V. After this has occurred, then

turn off the load switch. This will enable the fuel cell to become fully operational by itself before connection to the battery.

- 5) There is a battery regulator on the top part of the front side of the fuel cell. The fuel cell has a regulator at the back that regulates the hydrogen. It is therefore not necessary to regulate the pressure input of the hydrogen. The gage pressure reading on the hydrogen tank should be anywhere between 40-180 psi, but it is normally set to 120 psi.
- 6) The fuel cell has two outputs at the back for both the battery and the fuel cell; the blue connector at the back is for the battery and the red connector is for the fuel cell. The battery output gives a regulated constant output designed to charge Lead Acid batteries. The output for the fuel cell is the output directly from the fuel cell and is unregulated, it follows the polarization curve.
- 7) When the red alert light flashes then the fuel cell has encountered a problem and should automatically turn off. There should be an error message on the display. If not turn off the hydrogen and make sure the fuel cell is off. Normally the error LED will turn on when the hydrogen tank is empty, in that case just replace the tank and restart the fuel cell.
- 8) To turn off the fuel cell, just close the hydrogen tank and press the off switch.
- 9) Then to draw an output from the fuel cell, simply unplug the batteries from the back and turn the load switch on. Power can be drawn from the two leads of the FC.

10.2. DAQ System

The DAQ system is a portable data acquisition device that can take current, voltage and temperature readings for up to 40 channels at the same time. It is however, kind of clunky and hard to use, mostly because it is meant to be portable, and this application was new technology when the unit was purchased. The DAQ system needs to go through the following process for EVERY single run of data:

- 1) Power on DAQ power supply and turn on DAQ box
- 2) Plug in flash card to front
- 3) Connect it to computer via ethernet
- 4) Set local computers IP to : 192.92.103.xxx (xxx is anything between 120-220 (about))
- 5) Launch the VersaDAQ software.
- 6) Load config file of start new
- 7) Configure each channel (if not loaded)
- 8) Set number of samples and sample rate
- 9) Name output file

The DAQ starts via the attached trigger (little button with tiny wires going to DAQ).

The DAQ is now stand alone. After the DAQ has taken all of the samples as programmed, it turns itself off automatically. Then:

- 10) Take the flash card out and put in reader on second computer
- 11) Launch versaDAQ
- 12) Go to convert and the binary data file will be saved as a text file

For subsequent runs, the local IP address may need to be incremented, or simply reset the entire system

10.3. Procedure for Charging Batteries

Charging lithium-ion batteries involves using the MITS pro software in conjunction with the **charging machine**. Charging takes place in two steps: constant current and constant voltage. This document is designed to provide the procedure for using MITS pro to charge lithium-ion batteries.

The first step for using MITS pro is creating what is known as a schedule file. The schedule file is the program you feed into the charging machine to charge the batteries. To create a schedule file, first open the MITS pro software. On the left hand column, there is a list of files. Near the top is "Schedules." Right click on schedules, and select new schedule file. This will open a new window with the schedule. The correct format for the schedule file to charge the batteries is shown in table 6.

Table 6: Charging schedule for batteries

OCV	1	Rest				
Log Limit	Step Limit	Goto Step	Type 1	Sign 1	Value 1	
Check	Check	Next Step	PV_Chan_Step_Time	>=	00:00:05	
Chg_CC	2	Current (A)	10			High
Log Limit	Step Limit	Goto Step	Type 1	Sign 1	Value 1	
Check	Check	Next step	PV_Chan_Voltage	>=	16.8	
Check			DV_Time	>=	00:05:00	
Chg_CV	2	Voltage (V)	16.8			High
Log Limit	Step Limit	Goto Step	Type 1	Sign 1	Value 1	
Check	Check	End Test	DV_Chan_Current	<=	0.3	
Check			DV_Time	>=	00:05:00	

As shown in the schedule file above, a rest period is first specified for the batteries. This is the time between running the program and actual charging commencement. The next step is the constant current charging sequence. The constant current is specified as 10 amperes in row 4 in Table 6. The 6th row specifies that the constant current charging sequence is to run until the voltage reaches 16.8 volts. The 7th row is used for data acquisition. The DV_Time option allows the user to specify how often he/she wants to take a measurement of the current state in the battery. For this schedule, this time is set at 5 minutes, but the user can alter this time if desired. Once the constant current charging sequence is finished, the constant voltage charging sequence takes over.

Constant voltage is specified to take place at 16.8 volts in row 8 in Table 6. The end test command in row 10 is used to specify the condition when the charging

sequence should end. This condition is defined as when the current has reached a value of 0.3 amperes. Just as for the constant current charging sequence, a data acquisition time of 5 minutes has been specified for the constant voltage charging sequence. This is specified in the last row of Table 6. Before the actual testing procedure can be executed, additional parameters must be specified.

While in the schedule window, there is a “Global” tab at the bottom of the window. Click on this window and set the current use and voltage use to 105%. Also, under the auxiliary channel safety limit, select the temp option and make the limits from 0 to 80 °C. This condition specifies that if the temperature in the batteries reaches a temperature of 80 °C, then a warning from the computer will be displayed to end the schedule. Once these conditions have been specified, one more step is necessary to carry out the charging operation.

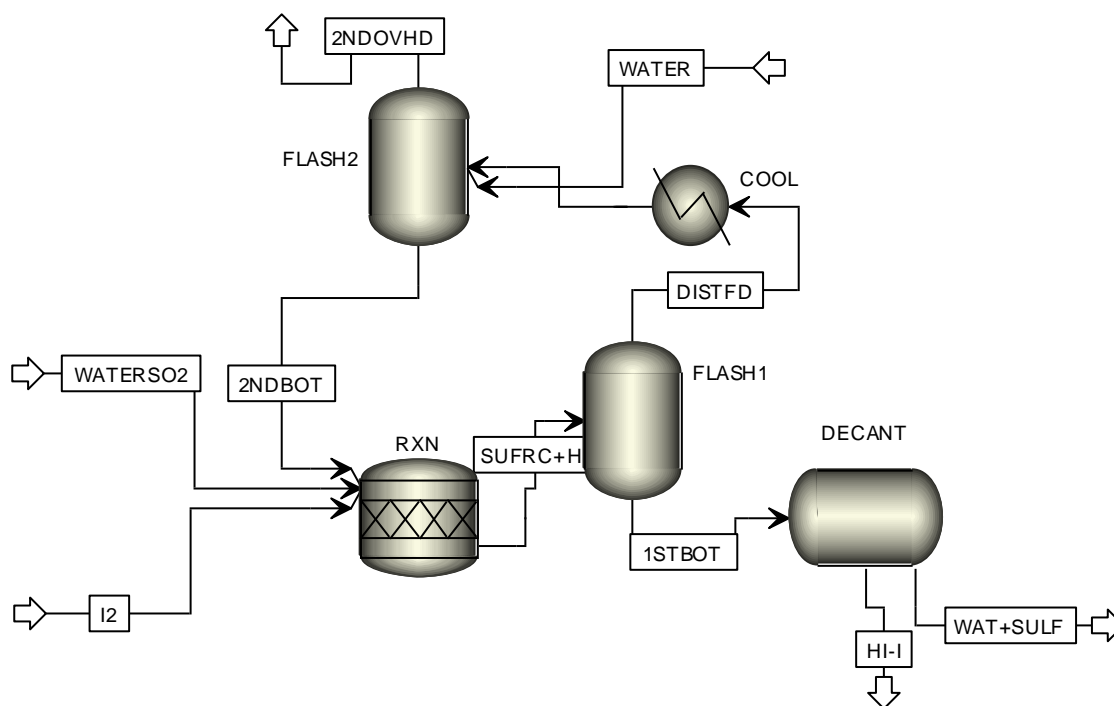
Go back to the original MITS pro application window, and scroll down until you see “Batch files” in the list of files on the left hand side. Double click “Batch files” and then double click “ArbinSys.bth.” This will open a batch window where the schedule is placed. For the charging machine, there are two channels available. In the batch file window, there are two channels to choose from. Chose one of them and right click on the schedule column for the appropriate column. Select the assign option which will bring up a list of possible schedule files. Select the name for the schedule file that was created for the charging sequence. Now save this file and go back to the main MITS pro application window. With the battery properly connected to the chosen channel, right click on the ArbinSys.bth file under the Batch file menu. Select launch to launch the schedule to charge the batteries. In the batch file window, the progress of the test can be viewed on the “brief view” window. Once the test is done, the brief view window will indicate the test is finished.

10.4. Detailed PFD's and Material Balances for Hydrogen from Non-Fossil Fuel Based Sources

All Material Balances are based on a hydrogen production rate of 1 lb-mol/h. Actual design basis is 1000 lb-mol/h.

Section I

Section I PFD



Section I Material Balances

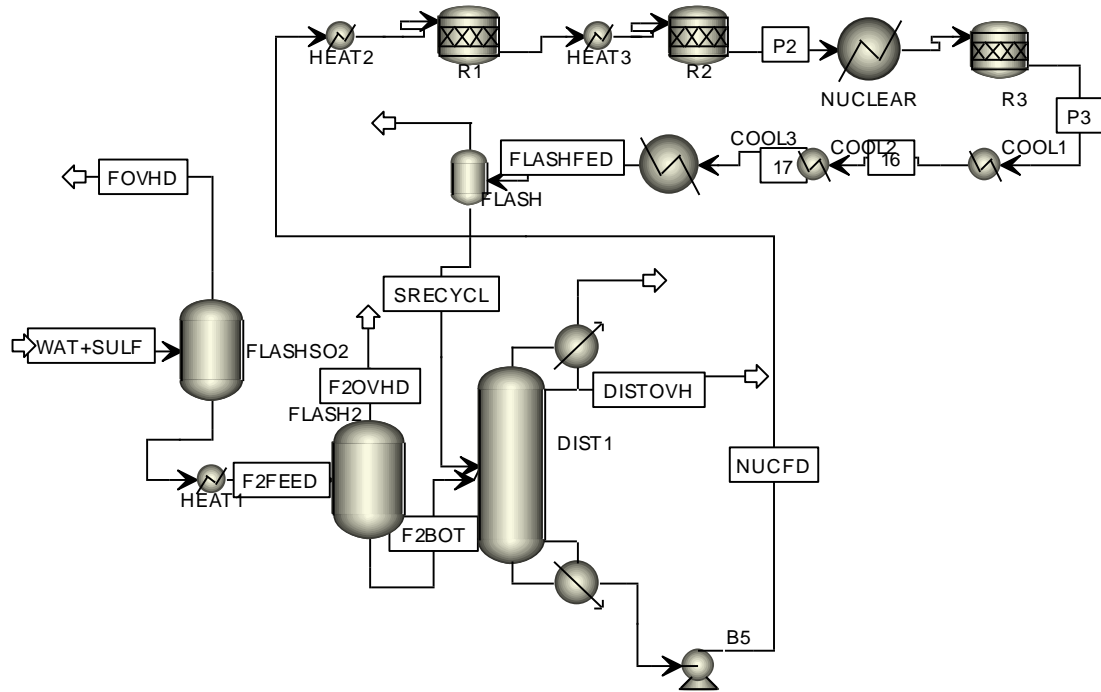
Section I										
	wat/SO2	I2	sulfrc+HI	distfd	1st bot	HI-I	Wat+Sulf	Water	2ndOvhd	2ndBot
Sulfuric Acid	0.000	0.000	0.001	0.000	0.001	0.001	0.000	0.000	0.000	0.000
HI	0.000	10.983	0.005	0.005	0.000	0.000	0.000	0.000	0.000	0.000
Iodine	0.000	49.000	47.466	0.022	47.444	37.535	9.910	0.000	0.000	0.022
Water	30.800	39.983	54.063	0.042	54.020	13.173	40.847	2.000	0.001	2.037
SO2	2.300	0.000	0.802	0.061	0.740	0.586	0.155	0.000	0.004	0.058
Oxygen	0.500	0.000	0.500	0.498	0.002	0.002	0.001	0.000	0.498	0.000
Hydrogen	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H3O+	0.200	0.017	15.867	0.000	15.867	0.001	15.867	0.000	0.000	0.005
I-	0.000	0.017	14.112	0.000	14.112	0.001	14.111	0.000	0.000	0.005
HSO4-	0.200	0.000	1.755	0.000	1.755	0.681	1.074	0.000	0.000	0.000
Total Flow lbmol/hr	34.00	100.00	134.57	0.63	133.94	51.98	81.96	2.00	0.50	2.13
Total Flow lb/hr	741	14564	15352	27	15326	9868	5458	36	16	47
Total Flow cuft/hr	95	984	125	47	78	44	34	1	26	1
Temperature F	248	248	248	248	248	248	248	100	40	40
Pressure psi	102	102	102	102	102	102	102	102	102	102
Vapor Frac	0.03	0.13	0.00	1.00	0.00	0.00	0.00	0.00	1.00	0.00
Liquid Frac	0.97	0.87	1.00	0.00	1.00	1.00	1.00	1.00	0.00	1.00
Solid Frac	0	0	0	0	0	0	0	0	0	0
Enthalpy Btu/lbmol	-120280	-41678	-56789	-17205	-56975	-31022	-83786	-122543	-1424	-122412
Enthalpy Btu/lb	-5516	-286	-498	-402	-498	-163	-1258	-6802	-44	-5570
Enthalpy Btu/hr	-4.1E+06	-4.2E+06	-7.6E+06	-1.1E+04	-7.6E+06	-1.6E+06	-6.9E+06	-2.5E+05	-7.1E+02	-2.6E+05
Entropy Btu/lbmol-R	-31.54	-3.17	-0.81	0.61	-0.82	-0.46	-15.45	-38.22	-4.26	-38.73
Entropy Btu/lb-R	-1.446	-0.022	-0.007	0.014	-0.007	-0.002	-0.232	-2.121	-0.132	-1.762
Density lbmol/cuft	0.357	0.102	1.077	0.013	1.711	1.175	2.390	3.442	0.019	3.266
Density lb/cuft	7.78	14.80	122.82	0.58	195.77	223.14	159.13	62.02	0.61	71.77
Average MW	21.8	145.6	114.1	42.8	114.4	189.8	66.6	18.0	32.2	22.0

Section I Major Equipment Size and Cost

Section I				
Label	Sulfuric Acid Reactor	Flash 1	Cool	Decant
Type	CSTR	flash drum	refridge for heat ex	horizontal tank
Flow rate	15350 lb/h, liq	47 cu ft/h vap		15300 lb/h liq
Temp, F	248	248	40	248
Press, psig	102	102	102	102
Size	5 x 10,000 gal	2 ft dia x 2.5 ft	add 2% to tot.	35,000 sq ft
Cost \$K	17000	17		6000
Matl of construct	alloy 20	alloy 20	CS	stainless
Energy Requirements (KW)	minimal	minimal	3500	minimal

Section II

Section II PFD



Section II Material Balances

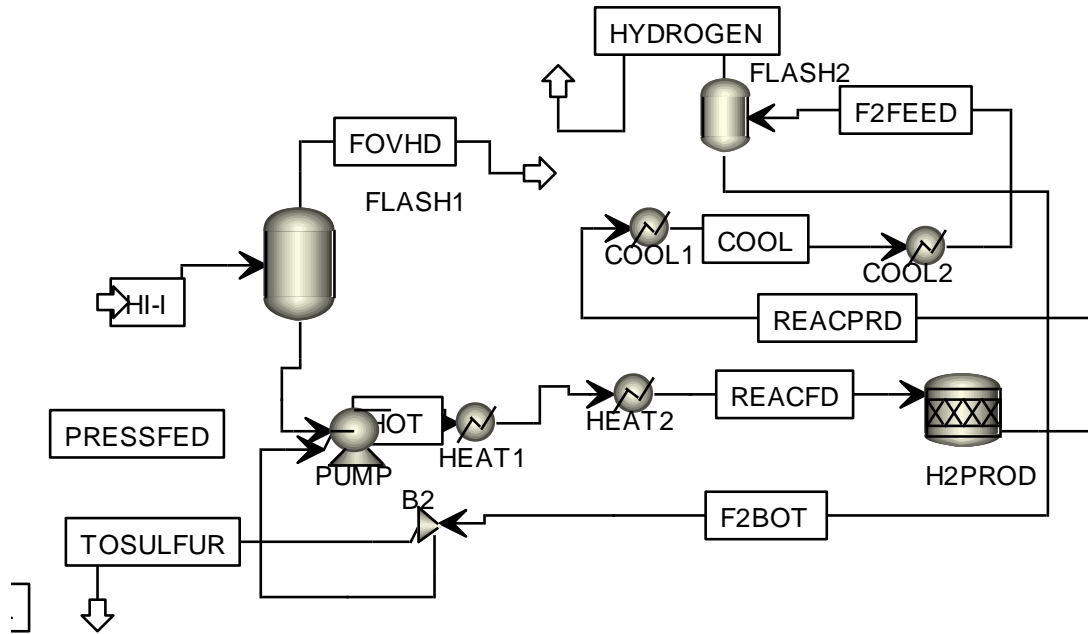
Section II													
	Wat+Sulf	Fovhd	Fbot	O2SO2	Srecyc	distovhd	distbot	nuclfeed	feed	12	P3	16	flashfeed
Sulfuric Acid	0.000	0.000	0.000	0.000	0.001	0.000	2.176	2.176	2.171	1.086	0.096	0.309	0.423
HI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Iodine	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Water	4.150	0.012	4.138	2.005	2.133	4.020	0.005	0.005	0.000	0.000	0.037	0.037	0.152
SO2	0.015	0.012	0.003	0.003	0.000	0.003	0.000	0.000	0.000	0.543	0.208	0.950	0.950
Oxygen	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.271	0.104	0.475	0.475
Hydrogen	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H3O+	0.950	0.000	0.950	0.000	0.949	0.000	0.257	0.257	0.261	0.804	0.438	1.174	1.060
I-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HSO4-	0.950	0.000	0.950	0.000	0.949	0.000	0.257	0.257	0.261	0.804	0.438	1.174	1.060
Total Flow lbmol/hr	6.07	0.02	6.04	2.01	4.03	4.02	2.69	2.69	2.69	3.51	1.32	4.12	4.12
Total Flow lb/hr	186	1	185	36	149	73	243	243	243	243	78	243	243
Total Flow cuft/hr	2	7	2	762	2	1	3	3	5	170	80	246	105
Temperature F	248	248	248	315	315	79	486	487	1112	1382	1652	1112	248
Pressure psi	102	26	26	22	22	1	1	102	102	102	102	102	102
Vapor Frac	0.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.24	0.26	0.36	0.34
Liquid Frac	1.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.76	0.74	0.64	0.66
Solid Frac	0	0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy Btu/lbmol	-159803	-114339	-159940	-102161	-177306	-122938	-315302	-315242	-260873	-230542	-218628	-117102	-192223
Enthalpy Btu/lb	-5210	-2791	-5222	-5652	-4808	-6812	-3491	-3491	-2889	-3324	-3722	-1982	-3254
Enthalpy Btu/hr	-9.7E+05	-2.8E+03	-9.7E+05	-2.1E+05	-7.1E+05	-4.9E+05	-8.5E+05	-8.5E+05	-7.0E+05	-8.1E+05	-2.9E+05	-4.8E+05	-7.9E+05
Entropy Btu/lbmol-R	-44.52	-1.30	-44.37	-8.38	-48.19	-39.05	-71.22	-71.14	-27.08	-18.61	-17.16	20.88	-42.71
Entropy Btu/lb-R	-1.451	-0.032	-1.449	-0.463	-1.307	-2.164	-0.789	-0.788	-0.300	-0.268	-0.292	0.353	-0.723
Density lbmol/cuft	2.675	0.003	2.685	0.003	2.357	3.451	1.057	1.056	0.599	0.021	0.016	0.017	0.039
Density lb/cuft	82.04	0.14	82.23	0.05	86.92	62.27	95.45	95.39	54.05	1.43	0.97	0.99	2.31
Average MW	30.7	41.0	30.6	18.1	36.9	18.0	90.3	90.3	90.3	69.4	58.7	59.1	59.1

Section II Major Equipment Size and Cost

Section II					
Label	Dist1	vac	Flash 2	cool1/2 heat 1/2	nuc 3
Type	Distillation Column, packed bed	2 stage steam ejector	flash drum	Heat exchanger	Heat exchange with nucl react
Flow rate	8,000 lbmol/h vap at R/R=1	vapor rate = 2 E6 cu ft/h	770 cu ft/h vap	243 lb/h	243 lb/h
Temp, F	100 - 486	100	315	1652 -->600	1200 --> 1652
Press, psig	-13 (100 torr)	-13 (100 torr)	102	330	330
Size	16 ft dia with 4 stages, 10 ft high	6x 2-stage ejectors	4 ft dia, 5 ft tall	A = 125,000 sq ft	A=15,000 sq ft
Cost \$K	400	120	60	300	100
Matl of construct	alloy G	CS	hastloy C	alloy 20	alloy G
Energy Requirements (KW)	55000	not calculated	minimal	minimal	12000

Section III

Section III PFD



Section III Material Balances

	Block for HI												
	HI-I	Fovhd	Fbot	Pressfd	Hot	Reacfd	Reacprd	Cool	F2feed	Hydrogen	F2bot	Recyc	ToSulf
Sulfuric Acid	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HI	2.590	0.031	2.554	2.913	0.001	0.112	0.146	11.545	0.480	0.000	0.480	0.048	0.432
Iodine	48.000	0.185	47.815	53.241	53.241	53.241	54.260	54.260	54.260	0.000	54.260	5.426	48.834
Water	56.130	0.585	55.541	62.013	59.101	59.212	61.284	72.683	61.618	0.000	61.618	6.162	55.456
SO2	1.370	1.235	0.135	0.150	0.150	0.150	0.150	0.150	0.150	0.006	0.143	0.014	0.129
Oxygen	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hydrogen	0.000	0.000	0.000	0.002	0.002	0.002	1.020	1.020	1.020	1.005	0.015	0.002	0.014
H3O+	9.870	0.000	9.874	10.670	13.582	13.471	11.400	0.000	11.065	0.000	11.065	1.107	9.959
I-	9.870	0.000	9.874	10.670	13.582	13.471	11.400	0.000	11.065	0.000	11.065	1.107	9.959
H2SO4-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total Flow lbmol/hr	127.83	2.04	125.79	139.66	139.66	139.66	139.66	139.66	139.66	1.01	138.65	13.86	124.78
Total Flow lb/hr	15053	141	14913	16570	16570	16570	16570	16570	16570	2	16567	1657	14910
Total Flow cuft/hr	133	526	76	84	2494	3469	3620	144	97	19	79	8	71
Temperature F	248	248	248	247	450	584	584	350	77	77	77	77	77
Pressure psi	102	29	29	319	319	319	319	319	319	319	319	319	319
Vapor Frac	0.01	1.00	0.00	0.00	0.69	0.79	0.82	0.01	0.01	1.00	0.00	0.00	0.00
Liquid Frac	0.99	0.00	1.00	1.00	0.31	0.21	0.18	0.99	0.99	0.00	1.00	1.00	1.00
Solid Frac	0	0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy Btu/lbmol	-57119	-103197	-56167	-56794	-43555	-33389	-34367	-56027	-63134	-818	-63588	-63588	-63588
Enthalpy Btu/lb	-485	-1495	-474	-479	-367	-281	-290	-472	-532	-335	-532	-532	-532
Enthalpy Btu/hr	-7.3E+06	-2.1E+05	-7.1E+06	-7.9E+06	-6.1E+06	-4.7E+06	-4.8E+06	-7.8E+06	-8.8E+06	-8.3E+02	-8.8E+06	-8.8E+05	-7.9E+06
Entropy Btu/lbmol-R	-7.43	5.04	-6.53	-7.38	7.27	16.52	15.43	-7.25	-17.14	-6.02	-17.22	-17.22	-17.22
Entropy Btu/lb-R	-0.063	0.073	-0.055	-0.062	0.061	0.139	0.130	-0.061	-0.144	-2.469	-0.144	-0.144	-0.144
Density lbmol/cuft	0.962	0.004	1.659	1.657	0.056	0.040	0.039	0.969	1.435	0.055	1.759	1.759	1.759
Density lb/cuft	113.28	0.27	196.63	196.62	6.64	4.78	4.58	115.02	170.28	0.13	210.23	210.23	210.23
Average MW	117.8	69.0	118.5	118.6	118.6	118.6	118.6	118.6	118.6	2.4	119.5	119.5	119.5

Section III Major Equipment Size and Cost

	Section III						
Label	Flash 1	Flash 2	Pump	Heat 2	Heat1/cool1	Cool 2	Cool 3
Type	flash drum	flash drum	centrif. Pump	heat exch	heat exch	heat exch w/ water	heat exch w/ chilled water
Flow rate	526 Cu Ft/h vap	18 cu ft/h vap	10.4 gpm	16570 lb/h	16570 lb/h	16570 lb/h	16570 lb/h
Temp, F	248	77	215	450 --> 584	248 --> 450, 574 --> 350	302-->130	302-->77
Press, psig	29	319	29 --> 319	319	319	319	319
Size	4 ft dia.	15 in	3 2-stage	35,000 sq ft	62,500 sq ft	62,500 sq ft	62,500 sq ft
Cost \$K	16	8	300	850	2800	2800	2800
Matl of construct	stainless	stainless	stainless	monel	monel	stainless	stainless
Energy Requirements (KW)	minimal	minimal	4500	400,000	minimal	minimal	35,000

Storage Equipment sizing and total cost

	Tankage				Sum of All Equipment
Label	Hydrogen	Sulfuric Acid	Iodine	aq HI	
Type	Press Vessel	horizontal tank	horizontal tank	horizontal tank	
Flow rate	12 h storage	for startup	for startup	for startup	
Temp, F	RT	RT	RT	RT	
Press, psig	320	atm	atm	atm	
Size	60 k cu ft, use 5 *100,000 gal	75,000 gal	35,000 cu ft	35,000 cu ft	
Cost \$K	2000	210	600	600	\$37,002
Matl of construct	ss	alloy 20	alloy	alloy	
Energy Requirements (KW)	minimal	minimal	minimal	minimal	470,000KW for heat, 40,000 KW for elect.

Working Capital – Chemical Start up Expense

Chemical	sulfuric acid	47% HI in water	I ₂
Quantity	50 k gal ~ 300 tons	1250 tons	2500 tons
Price Per Unit	\$57/ton from Chem Mkt rep	\$10/kg (estimate from I ₂ Price)	\$13/kg (from chem mkt rep)
Total Cost (\$K)	\$27 K	\$12,000	\$32,000

Example Calculations Distillation Tower Sizing

<p>This spreadsheet calculates the column diameter, mainly as a function of the volumetric flow rate of vapor. The X and Y value are compared to the Eckert Correlation, found on pg 480 of "Distillation Design" by H. Z. Kister 1992 McGraw Hill</p>					
L (liq flow rate, lb/s-ft ²)	G (vapor flow rate, lb/s-ft ²)	rho-L (lb/ft ³)	rho-G ¹ (lb/ft ³)	rho-Water	F (packing factor)
0.124	0.124	78.0	0.0043	62.4	40
gc	X coordinate for correl	Y coordinate for correlation	Fg (vapor flow rate, lb/h)	Fl (liq flow rate, lb/h)	column area (ft ²)
32.2	0.0074	0.0443	90000	90000	201.0
mu-L (c-Poise)	Psi (wat density/liq dens)	lb mol/h from simulation	scale up (simulation to actual)		
0.84	0.800	5	1,000		
column diam (ft)					
16					
¹ at 100 mm					

Distillation Tower Cost Estimate from 494 Text

This spreadsheet estimates the cost of the distillation tower from pgs 527 - 536 of Product and Process Design Principles by Seider et. al. 2004				
<i>Note: The value of \$240K from this spreadsheet was much lower than estimates from Aspen Icarus Cost Estimator, so the value of \$600K was used for the design estimate.</i>				
te min tower thickness	Em	L (in.)	Di (in.)	Pd , operating press., equiv to vac design
0.92	3.00E+07	96	192	50
	Fm vessel matl of const fact	CpL cost of platforms and ladders	Vp packing vol, cu ft	Cpk packing cost per cu ft
	4	\$7,175	1608	\$100
Cv cost of empty tower if carbon steel	Cdr cost of distributors		W vessel wt., lb	ts actual tower thickness, in.
\$13,205	\$1,631		43985.9	1.02
Cp total purchased cost	PACKING COST			
\$233,516	\$160,768			

Heat Exchanger for Section III Heat1/Cool1

Estimate for Cost of Heat Exchanger (from Product and Process Design Principles, by Seider et. al.)			
<i>Note: the larger figure of \$2800 K was used based on results from Aspen Icarus Cost Estimator</i>			
A area, sq ft	Q BTU/h transferred from simulation	U const	delta T deg F
62500	2.50E+06	200	200
scale fact simulation to design	Cb cost if carbon steel	FM matl of construct fact	Cp purchase price
1000	\$422,393	4	\$1,689,573

10.5. Sizing and Costing of Hydrogen Production from Natural Gas

Sample calculations for the sizing and costing of the hydrogen production plant from natural gas.

- **Sizing the purification reactor**

- Assumptions/Knowns

$$t_{res} = 120s$$

$$D_i = 1m$$

$$\dot{V} = 46.113m^3/h$$

- Reactor cross-sectional area

$$Area = \pi r^2$$

$$= (0.5m)^2 \pi = 0.785m^2$$

- Superficial velocity of fluid in reactor

$$\begin{aligned} Velocity &= \frac{\dot{V}}{Area} \\ &= \frac{46.113m^3/h}{0.785m^2} \left(\frac{1h}{3600s} \right) \\ &= 0.0163m/s \end{aligned}$$

- Determine length of reactor

$$Length = t_{res} * Velocity$$

$$= 120s * 0.016309m/s$$

$$= 1.957m$$

- **Sizing the methane reformer**

- Rate law

$$\begin{aligned} DEN &= 1 + K_{CO}P_{CO} + K_{H_2}P_{H_2} + K_{CH_4}P_{CH_4} + K_{H_2O}P_{H_2O} / P_{H_2} \\ &= 1 + 297(0.32) + 437(1.6) / 0.06 \\ &= 10,882 \end{aligned}$$

$$r_1 = \frac{\frac{k_1}{P_{H_2}^{2.5}} \left(P_{CH_4}P_{H_2O} - \frac{P_{H_2}^3 P_{CO}}{K_1} \right)}{(DEN)^2}$$

$$\begin{aligned} &= \frac{4153}{0.06^{2.5}} \left(0.32(1.6) - \frac{0.06^3(0)}{32.77} \right) \\ &= \frac{(10,882)^2}{} \\ &= -0.0167 \text{ kgmol/kg}_{cat} \cdot h \end{aligned}$$

- Mass of catalyst

$$\begin{aligned} W &= \int_{F_{A0}}^{F_A} \frac{F_A'}{r_1} = \frac{F_A - F_{A0}}{r_1} \\ &= \frac{(3.95 - 735) \text{ kgmol/h}}{-0.0167 \text{ kgmol/kg}_{cat} \cdot h} \\ &= 44,000 \text{ kg}_{cat} \end{aligned}$$

- Volume of catalyst

$$v = \frac{W}{\rho} = \frac{44,000 \text{ kg}}{1,050 \text{ kg/m}^3} = 41.77 \text{ m}^3$$

- Volume of reactor

$$V = \frac{v}{1 - \varepsilon} = \frac{41.77 \text{ m}^3}{1 - 0.528} \approx 88 \text{ m}^3$$

- **Sizing the water-gas shift reactor**

- Rate law

$$\begin{aligned} DEN &= 1 + K_{CO}P_{CO} + K_{H_2}P_{H_2} + K_{CH_4}P_{CH_4} + K_{H_2O}P_{H_2O} / P_{H_2} \\ &= 1 + 59.9(0.24) + 0.14(0.77) \\ &= 15.5 \end{aligned}$$

$$\begin{aligned} r_2 &= \frac{k_2 \left(P_{CO}P_{H_2O} - \frac{P_{H_2}P_{CO_2}}{K_2} \right)}{(DEN)^2} \\ &= \frac{5.089 \left(0.24(0.002) - \frac{0.77(0.98)}{17.87} \right)}{(15.5)^2} \\ &= -0.00114 \text{ kgmol/kg}_{cat} \cdot h \end{aligned}$$

- Mass of catalyst

$$\begin{aligned} W &= \int_{F_{A0}}^{F_A} \frac{F_A}{r_2} = \frac{F_A - F_{A0}}{r_2} \\ &= \frac{(58.52 - 731.48) \text{ kgmol/h}}{-0.00114 \text{ kgmol/kg}_{cat} \cdot h} \\ &\approx 588,000 \text{ kg}_{cat} \end{aligned}$$

- Volume of catalyst

$$v = \frac{W}{\rho} = \frac{588,000 \text{ kg}}{1,050 \text{ kg/m}^3} = 560 \text{ m}^3$$

- Volume of reactor

$$V = \frac{v}{1 - \varepsilon} = \frac{560 \text{ m}^3}{1 - 0.528} \approx 1,200 \text{ m}^3$$

- **Costing the natural gas**

$$Cost_{nat-gas} = \dot{V} \delta_{ng}$$

- $$\begin{aligned} &= (41.572 \text{ m}^3/h) \left(\frac{\$6.28}{1000 \text{ ft}^3} \right) \left(\frac{35.3145 \text{ ft}^3}{1 \text{ m}^3} \right) \\ &= \$9.22/h \\ &\approx \$78,000/yr \end{aligned}$$

- **Costing the catalyst**

- For methane reformer

$$\begin{aligned} Cost_{catalyst} &= V\delta_{cat} \\ &= (41.77m^3) \left(\frac{\$650}{1ft^3} \right) \left(\frac{35.3145ft^3}{1m^3} \right) \\ &\approx \$960,000 \end{aligned}$$

- For water-gas shift reactor

$$\begin{aligned} Cost_{catalyst} &= V\delta_{cat} \\ &= (559.85m^3) \left(\frac{\$650}{1ft^3} \right) \left(\frac{35.3145ft^3}{1m^3} \right) \\ &\approx \$12,900,000 \end{aligned}$$

- **Costing the purification reactor**

- Design pressure

$$\begin{aligned} P_d &= \exp \left\{ 0.60608 + 0.91615[\ln(P_0)] + 0.0015655[\ln(P_0)]^2 \right\} \\ &= \exp \left\{ 0.60608 + 0.91615[\ln(21.6)] + 0.0015655[\ln(21.6)]^2 \right\} \\ &= 31psig \end{aligned}$$

- Wall thickness

$$\begin{aligned} t_p &= \frac{P_d D_i}{2SE - 12.P_d} \\ &= \frac{31psig(3.2808ft)}{2(3800psig)(0.85) - 1.2(31psig)} \\ &= 0.0158ft \end{aligned}$$

Since t_p is too small, 0.03125ft will be used.

- Shell thickness

$$\begin{aligned} t_s &= t_p + t_c \\ &= 0.03125ft + 0.0104ft \\ &= 0.0417ft \end{aligned}$$

- Weight of empty vessel

$$\begin{aligned} W &= \pi(D_i + t_s)(L + 0.8D_i)t_s\rho \\ &= \pi(3.2808ft + 0.0417ft)(6.42ft + 0.8(3.2808ft))(0.0417ft)490lb/ft^3 \\ &= 1,927lb \end{aligned}$$

- Empty vessel cost

$$\begin{aligned}
 C_v &= \exp \left\{ 8.717 - 0.2330[\ln(W)] + 0.04333[\ln(W)]^2 \right\} \\
 &= \exp \left\{ 8.717 - 0.2330[\ln(1927)] + 0.04333[\ln(1927)]^2 \right\} \\
 &= \$12,502
 \end{aligned}$$

- Added cost

$$\begin{aligned}
 C_{PL} &= 1,580(D_i)^{0.20294} \\
 &= 1,580(3.2808)^{0.20294} \\
 &= \$2,011
 \end{aligned}$$

- Purchase cost

$$\begin{aligned}
 C_p &= F_M C_v + C_{PL} \\
 &= 1(\$12,502) + \$2,011 \\
 &\approx \$14,500
 \end{aligned}$$

- **Costing the methane reformer (Price assuming a 2-m diameter)**

- Design pressure

$$\begin{aligned}
 P_d &= \exp \left\{ 0.60608 + 0.91615[\ln(P_0)] + 0.0015655[\ln(P_0)]^2 \right\} \\
 &= \exp \left\{ 0.60608 + 0.91615[\ln(14.31)] + 0.0015655[\ln(14.31)]^2 \right\} \\
 &= 21 \text{ psig}
 \end{aligned}$$

- Wall thickness

$$\begin{aligned}
 t_p &= \frac{P_d D_i}{2SE - 12.P_d} \\
 &= \frac{21 \text{ psig}(6.56 \text{ ft})}{2(5200 \text{ psig})(0.85) - 1.2(21 \text{ psig})} \\
 &= 0.0156 \text{ ft}
 \end{aligned}$$

Since t_p is too small, 0.03125ft will be used.

- Shell thickness

$$\begin{aligned}
 t_s &= t_p + t_c \\
 &= 0.03125 \text{ ft} + 0.0104 \text{ ft} \\
 &= 0.0417 \text{ ft}
 \end{aligned}$$

- Weight of empty vessel

$$\begin{aligned}
 W &= \pi(D_i + t_s)(L + 0.8D_i)t_s \rho \\
 &= \pi(6.56 \text{ ft} + 0.0417 \text{ ft})(92 \text{ ft} + 0.8(6.56 \text{ ft}))(0.0417 \text{ ft})490 \text{ lb/ft}^3 \\
 &= 41,200 \text{ lb}
 \end{aligned}$$

- Empty vessel cost

$$\begin{aligned}
 C_V &= \exp \left\{ 8.717 - 0.2330[\ln(W)] + 0.04333[\ln(W)]^2 \right\} \\
 &= \exp \left\{ 8.717 - 0.2330[\ln(41200)] + 0.04333[\ln(41200)]^2 \right\} \\
 &= \$68,000
 \end{aligned}$$

- Added cost

$$\begin{aligned}
 C_{PL} &= 1,580(D_i)^{0.20294} \\
 &= 1,580(6.56)^{0.20294} \\
 &= \$2,300
 \end{aligned}$$

- Purchase cost

$$\begin{aligned}
 C_P &= F_M C_V + C_{PL} \\
 &= 1(\$41,200) + \$2,300 \\
 &\approx \$70,700
 \end{aligned}$$

- **Costing the water-gas shift reactor (Price assuming a 2-m diameter)**

- Design pressure

$$\begin{aligned}
 P_d &= \exp \left\{ 0.60608 + 0.91615[\ln(P_0)] + 0.0015655[\ln(P_0)]^2 \right\} \\
 &= \exp \left\{ 0.60608 + 0.91615[\ln(14.31)] + 0.0015655[\ln(14.31)]^2 \right\} \\
 &= 21 \text{ psig}
 \end{aligned}$$

- Wall thickness

$$\begin{aligned}
 t_p &= \frac{P_d D_i}{2SE - 12.P_d} \\
 &= \frac{21 \text{ psig}(6.56 \text{ ft})}{2(5200 \text{ psig})(0.85) - 1.2(21 \text{ psig})} \\
 &= 0.0156 \text{ ft}
 \end{aligned}$$

Since t_p is too small, 0.03125ft will be used.

- Shell thickness

$$\begin{aligned}
 t_s &= t_p + t_c \\
 &= 0.03125 \text{ ft} + 0.0104 \text{ ft} \\
 &= 0.0417 \text{ ft}
 \end{aligned}$$

- Weight of empty vessel

$$\begin{aligned}
 W &= \pi(D_i + t_s)(L + 0.8D_i)t_s \rho \\
 &= \pi(6.56 \text{ ft} + 0.0417 \text{ ft})(1240 \text{ ft} + 0.8(6.56 \text{ ft}))(0.0417 \text{ ft})490 \text{ lb/ft}^3 \\
 &= 527,000 \text{ lb}
 \end{aligned}$$

- Empty vessel cost

$$C_V = \exp \left\{ 8.717 - 0.2330[\ln(W)] + 0.04333[\ln(W)]^2 \right\}$$

$$= \exp \left\{ 8.717 - 0.2330[\ln(527000)] + 0.04333[\ln(527000)]^2 \right\}$$

$$= \$524,000$$

- Added cost

$$C_{PL} = 1,580(D_i)^{0.20294}$$

$$= 1,580(6.56)^{0.20294}$$

$$= \$2,300$$

- Purchase cost

$$C_P = F_M C_V + C_{PL}$$

$$= 1(\$524,000) + \$2,300$$

$$\approx \$526,000$$

Table 7: Cost of each vessel and its corresponding catalyst

Reactor Cost	Empty Vessel Inner Diameter			Catalyst Mass (kg)	Cost of Catalyst
	1 m (3.28 ft)	2 m (6.56 ft)	2.5 m (8.20 ft)		
Purification	\$ 14,513.29	--	--	--	--
Reformer	--	\$ 70,744.13	\$ 69,051.11	43,855.81	\$ 958,747.52
Water-Gas Shift	--	\$ 526,260.15	\$ 479,882.21	587,842.10	\$ 12,851,026.05

Table 8: Estimated cost of plant

	Costed	Costed x 2	Costed x 3	Costed x 4	Costed x 5
Capital Cost	\$ 14,373,220.19	\$ 28,746,440.37	\$ 43,119,660.56	\$ 57,492,880.74	\$ 71,866,100.93
Utilities	\$ 3,578,000.00	\$ 7,156,000.00	\$ 10,734,000.00	\$ 14,312,000.00	\$ 17,890,000.00

Table 9: Annual costs for each of the multiples of the costed column from Table 8, based on different interest rates

Interest Rate	Annual Cost to Produce Hydrogen			
10%	\$ 10,030,644.04	\$ 15,045,966.06	\$ 20,061,288.07	\$ 25,076,610.09
20%	\$ 12,905,288.07	\$ 19,357,932.11	\$ 25,810,576.15	\$ 32,263,220.19
30%	\$ 15,779,932.11	\$ 23,669,898.17	\$ 31,559,864.22	\$ 39,449,830.28

Table 10: Minimum cost of hydrogen to the consumer, based on annual costs in Table 9

Interest Rate	Minimum Cost of Hydrogen per kilogram			
10%	\$ 0.20	\$ 0.31	\$ 0.41	\$ 0.51
20%	\$ 0.26	\$ 0.40	\$ 0.53	\$ 0.66
30%	\$ 0.32	\$ 0.48	\$ 0.64	\$ 0.81