Design Proposal for a Hydrogen Fueling Station

(Arcata, CA)

H_2 - *Go!* Inc.

February 29, 2004

Executive Summary

Increased atmospheric CO_2 concentrations in combination with limited fossil fuel reserves have helped to stimulate an interest in hydrogen as an energy carrier. The concept of a hydrogen economy, where energy can be produced and distributed locally is an attainable goal. The objective of this proposal is to provide the complete and detailed design specifications for a hydrogen fueling station, built and maintained by *H_2-Go!* Incorporated. The station will be located in Arcata, California on a brown-field site in an industrial-commercial zone. The hydrogen fuel will be produced on-site via electrolysis and will be stored as a compressed gas at high pressures.

The energy consumed by the *H_2-Go!* fueling station will be supplied by Fairhaven, a local power plant and a U.S. Department of Energy certified renewable energy source. A Direct Access contract will be arranged with Fairhaven for a selling price of approximately $0.0647/kWh. Pacific Gas and Electric (PG&E) will provide transmission and distribution services under the E-19, Primary, Firm, Continuous Direct Access rate schedule. Kneaper Electric Company will install a 480V, 3-phase transformer and electrical service connection to the building that houses the gas generation plant. As an alternative, an electrical service plan will be constructed using the E-19 Primary, Firm, Bundled rate schedule and Green-e tags from the Bonneville Environmental Foundation. This secondary alternative is included for design flexibility and allows for expansion or replication.

Hydrogen gas generation will be accomplished through the use of two TITAN ™ EC-750 electrolyzers, produced by Teledyne Energy Systems. The combined maximum hydrogen production rate of the generators will be 84 Nm^3/hr. Each TITAN™ EC-750 will be coupled to a triple diaphragm compressor. The compressors are capable of 6,000 psig. The compressors will be supplied by Teledyne Energy Systems. The compressed hydrogen will be stored in six seamless carbon steel vessels built to ASTM standards. Discharge from the storage tanks will follow a cascade algorithm, effective at minimizing residual hydrogen fuel in the tanks and maximizing compressor energy efficiency. Fuel transfer from storage tanks to vehicles will be accomplished by a dispensing unit provided by Fueling Technologies Inc.

An economic analysis of the fueling station determines that the hydrogen produced can be sold for $18.57/kg, resulting in a consumer cost of $0.31/mile. A well to wheels analysis reveals that approximately 59.8 metric tons of GHG emissions can be saved annually if 50 conventional gasoline vehicles are replaced by 50 FCVs fueled by the *H_2-Go!* station. In order to address public concerns and integrate the fueling station into the community, a marketing and education strategy is also included.

The projected success behind the *H_2-Go!* fueling station design is based on hydrogen produced on site using clean energy. This design can be easily replicated and sited anywhere in the United States, independent of existing hydrogen infrastructure. *H_2-Go!* Inc. supports hydrogen as a fuel and with this fueling station design and we will help to facilitate the development of a hydrogen based economy.

Notation

CO_2 – Carbon Dioxide
TES – Teledyne Energy Systems
ASTM – American Society for Testing and Materials
FCV – Fuel Cell Vehicle
WTW – Well-to-wheel
PLC – Programmable Logic Controller
IQA – Instrument Quality Air
H_2 – Hydrogen
PRD – Pressure Relief Device
PDP – Power Distribution Panel
NEC – National Electric Code
NFPA – National Fire Protection Association
mmBtu – million British Thermal Unit
DOE – Department of Energy
GHG – Greenhouse Gas
WTT – Well-to-tank
HHV – Higher Heating Value
GGE – Gallon of Gasoline Equivalent
ZEV – Zero Emission Vehicle
gpm – gallons per minute

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1 Technical Design

1.1 Design Criteria

The primary design criteria used in developing this proposal are as follows:

- The refueling station must be able to refuel fifty cars per day (minimum) with three kilograms of hydrogen (H_2) delivered per car
- The three kilograms of H_2 are to be stored onboard the vehicle at a maximum pressure of 5,000 psig
- The station must be able to handle a single peak fueling period of 20 cars in one hour
- The maximum footprint of the station cannot exceed 14,440 ft^2
- The station must be accessible to the general public

Additional criteria were developed by the design team to facilitate selection of the most appropriate hydrogen production and distribution methods. These additional criteria are as follows:

- The production method will minimize well to tank carbon dioxide emissions
- The choice of production method will facilitate a reasonable rate of return on capital investment
- The station will safely provide an uninterrupted supply of hydrogen fuel to the citizens of the Arcata/Eureka area for a minimum of ten years
- The station design will be modular, thus enabling “carbon copies” to be quickly built as demand for hydrogen powered transportation increases.
- The station design will allow for CO_2-free production regardless of geographic location through utilization of Green-e certified electricity.

1.2 Station Site Plan

The hydrogen fueling station will be built and operated in Arcata, CA (north of Eureka on Highway 101). An aerial view of the station site is shown in **Figure 1**.

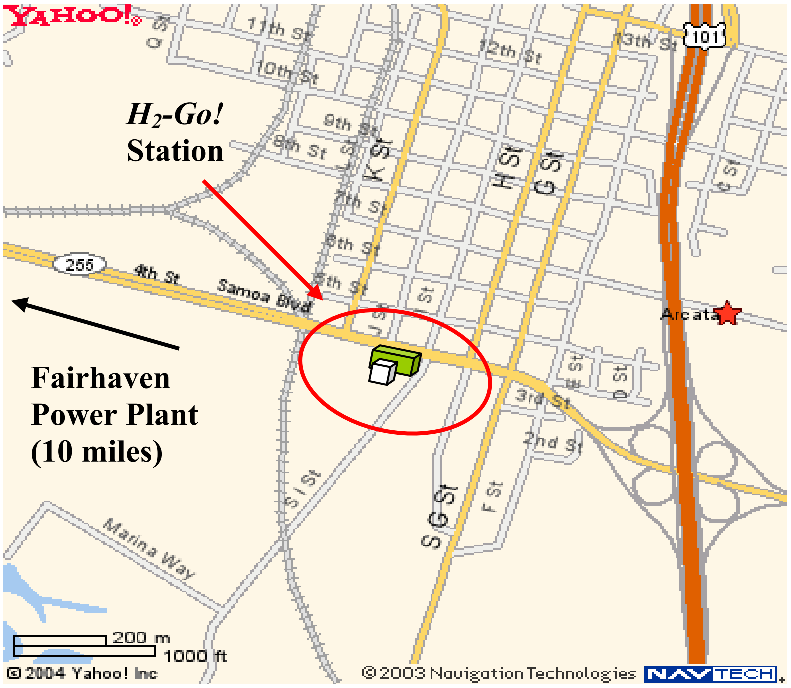


Figure 1- Location of hydrogen fueling station (Yahoo!, 2004).

The location shown in **Figure 1** was chosen for a number of reasons. It is located within an industrial-commercial permitting zone. This particular zone allows for the construction of fueling stations, as well as some fuel production industries, including hydrogen (Conlon, 2004). The plot where the station will be located is a certified brown field site. Constructing and operating a hydrogen fueling station would be considered by the City of Arcata to be a "beneficial use" of the site and would be an improvement upon its current condition. The site is located on Highway 255, just 10 miles east of the Fairhaven power plant, a designated renewable energy facility (USDOE, 2000). The fueling station site is near the 101/255 junction and is located in an area where many other fueling stations presently exist. A computer generated plan-view of the station site is located in **Appendix A**.

1.3 Hydrogen Production

On-site electrolysis is the method of hydrogen production that will most effectively satisfy the design criteria. The scale of demand specified in the request for proposal limited the field of electrolyzer manufacturers to Norsk Hydro of Sweden, Stuart Energy of Canada, and Teledyne Energy Systems Inc. (TES) of the USA. Two of TES's TITAN^{TM} EC-750 alkaline electrolyzers were determined to best meet the production requirements of the station. With over 35 years of experience in the hydrogen production field, TES systems have developed a reputation for manufacturing safe and reliable alkaline electrolyzers. The TITAN^{TM} EC-750 is currently the largest alkaline electrolyzer produced by TES. Each TITAN^{TM} EC-750 supplies 99.9999% pure H_2 at a rate of 42 Nm^3/hr at an operator selected delivery pressure of 10 to 115 psig. The combined hydrogen production rate of the electrolyzers is $84 Nm^3/hr$. The nominal conversion efficiency of the EC-750 is 5.6 $\frac{kWh}{Nm^3 H_2}$.

Each TITAN^{TM} EC-750 consists of two components, a gas generator and a matched power supply. System controls and instrumentation are located within the gas generator cabinet. A programmable logic controller (PLC) located on the gas generator cabinet monitors operational parameters and facilitates process control. The amount of gas produced is directly proportional to the amount of current applied across the cells of the generator. The PLC controls gas production by remote signaling of the power supply, located in a separate electrical control room. The Power supply converts AC electricity to the DC electricity necessary for the electrolysis process. The TITAN^{TM} EC-750 is designed for continuous automated operation. Upon startup, a nitrogen re-pressurization sequence brings the system up to pressure prior to hydrogen gas generation. Gas generation then automatically proceeds according to station demand as interpreted by the PLC. The outputs of the gas generator are pure oxygen gas, which is vented to the atmosphere, and pure hydrogen gas at a ratio of 2 parts H_2 to 1 part O_2.

Each TITAN^{TM} EC-750 consumes 0.183 gpm of feed water, which is provided by the station's water purification system to meet the ASTM D1193 (Type II) standard for feed water. The control system of each gas generator also uses instrument quality air (IQA) at a rate of 1.6 Nm^3/hr. One Kaeser SX-6 rotary screw compressor generates the control air supply. The SX-6 is capable off generating IQA at up to 205 psig. The maximum volumetric flow rate at this pressure is 22 Nm^3/hr. Additionally, a pressurized nitrogen supply provides each EC-750 with 1.2 Nm^3 of pre-pressurization gas for each startup. Descriptions of the aforementioned subsystems of the electrolysis unit can be found in **Section 1.7**.

1.4 Hydrogen Compression

At the *H_2-Go!* fueling station, two triple diaphragm compressors provided by TES will be used to compress hydrogen from 115 psig to 6,000 psig. When the pressure on the downstream side of the compressor drops below 5,990 psig, the compressor start up will be initiated by a signal from a pressure switch on the downstream side of the compressor. Another pressure switch located upstream of the compressor monitors suction pressure and will shut off the compressor if this pressure drops too low. Ballast tanks are incorporated into the line between the electrolyzer and the compressor whose function is described in **Section 1.9.1**. There are eight ballast tanks used within this system, each with a volume equal to 44 liters of water (Pacific Cylinders, 2004).

The TES triple diaphragm compressors are designed to deliver 6,000 psig hydrogen gas at 1,600 standard cubic feet per hour (scfh). The power consumption for this performance is approximately 5 kW per compressor. The differential temperature between inlet and outlet is approximately -9.5° C.

1.5 Hydrogen Storage

The on-site storage of hydrogen is a critical aspect of fueling station design and construction. Storage tanks serve two major roles in hydrogen delivery: regulation of delivery flow rate and increased working capacity.

A station designed around the use of eletrolyzers for its hydrogen production becomes highly dependent upon the hydrogen production rate of the electrolyzers. The request for proposal (Rules, 2004) indicates that the proposed station must be able to meet or exceed a demand of 50 cars/day (150 kg/day) and a one-time peak demand of nearly 7 cars/hr (20 kg/hr). With a hydrogen production rate of 7.06 kg/hr (two Teledyne TITAN^{TM} EC-750 hydrogen generators) and a 14 hr business day, storage is a necessary component for consistently meeting peak station demands.

Simulations of the tank charging and discharging rates, using worst-case demand scenarios, indicate that six 4m^3 tanks (at 6,000 psig) would be optimum storage for meeting consistent demands of up to 56 cars per day. The station also has the flexibility to meet holiday peaks and large day-to-day fluctuations exceeding 100 cars per day. The flexibility of the storage system is a result of a cascade discharge algorithm.

The six storage tanks will be stored outside in a semi-enclosed area at the rear of the station (**Appendix F**). The tanks are designed and constructed for high-pressure storage. They are made from seamless carbon-steel. Each tank meets the 1998 ASME safety standard codes, Section 7, Division 1, Addendum 1999. These tanks will be similar in size and shape to those used at the FreedomCAR fueling station in Arizona (Karner et al., 2003).

1.6 Hydrogen Dispensing

Hydrogen dispensing is not quite as simple as "pumping gas", and gasoline pumps are not capable of handling and dispensing hydrogen without a serious retrofit. Some researchers have suggested that the current natural gas infrastructure and existing dispensers could be retrofitted to accommodate hydrogen dispensing (Campbell, 2000). However, there are many differences between natural gas and hydrogen that must be considered before dispensing. A brief overview of the properties of hydrogen and natural gas are listed in **Table 1**.

Table 1- Comparison of natural gas and hydrogen (Campbell, 2000).

	Hydrogen	**Natural Gas**
Odor	Odorless	Mercaptan
Specific gravity (air = 1)	0.07	0.424
Heat value (kJ/kg)	119,972	50,020
Flammability Range in air	4% - 75%	5.3% - 15%
Ignition energy (mJ)	0.02	0.29
Flame color	Invisible	Visible

Industrially produced hydrogen dispensers bare a distinct resemblance to their gasoline dispensing forefathers, but their features and characteristics are much different. One (1) hydrogen dispenser was chosen for the *H_2-Go!* fueling station and is manufactured by Fueling Technologies Inc. (FTI). FTI is a company that has supplied dispensers for many different groups, such as the Sunline Transit Agency and the FreedomCAR pilot-study fueling station in Arizona. The FTI hydrogen dispenser is a one-size-fits-all model with a maximum dispensing pressure of 6,480 psig and a maximum mass flow rate of 22.7 kg/min. Ideally the dispenser could refuel a car with 3kg of hydrogen in as little as 8 seconds. However, under actual conditions and allowing for changes in storage tank pressures, fueling time is estimated at an average of 30 seconds to 1 minute per vehicle. The dispenser is capable of fueling two vehicles at a time, from either side of the dispenser (**Figure 12, Appendix G**).

A central Programmable Logic Controller (PLC) unit will be used as a central computer for controlling major functions of the station, including the control and regulation of the storage-dispenser interaction. Each station storage tank is equipped with pressure transducers and solenoid valves that will communicate with the PLC to allow for cascade dispensing of the hydrogen. The algorithms used with the PLC for charging and discharging of the tanks are listed in **Appendices D** and **E**. A description of the control system is provided in **Section 1.9**.

1.7 Auxiliary Systems

1.7.1 Control Air

The control air system delivers IQA to the hydrogen generator. The Keaser system includes a model SX-6 5Hp Rotary Screw Compressor, TA-5 Cycling Refrigerated Air Dryer, KOR-20 Coalescing Oil Removal Filter and a Demand Actuated Electronic Tank Drain. These components are mounted and plumbed to an 80 gallon horizontal deck tank. This system will provide compressed air at 120 scf per hour running for approximately 21 hours a day.

1.7.2 Nitrogen

The two TITAN^{TM} EC-750 generators require the purging of nitrogen gas during start-up from full shut down. The nitrogen system consists of standard cylinders, pressure regulators, piping network, and dual bank switching manifolds. The piping network and switching manifold distributes nitrogen to purge locations throughout the generation system. Based on manufacturer specified maintenance intervals, each gas generator will be shut down approximately four times per year for service. Upon restart, each gas generator consumes 40 scf of nitrogen gas. The resulting total demand for nitrogen per year is 320 scf. The nitrogen will be delivered to the station by Eureka Oxygen (Collins, 2004).

1.7.3 Helium

Vented hydrogen is directed through high and low pressure stacks designed to dispose of hydrogen gas. Of all the locations in the fueling station, the vents possess the highest probability of harboring a hydrogen flame. A thermocouple is installed in the vent stack to detect the presence of a hydrogen flame. If a flame is detected, the control system opens a solenoid valve to introduce helium into the lining of the stacks thereby extinguishing the flame.

1.7.4 Water Purification

Water for the electrolyzers is supplied by the city of Arcata at pressures between 80 and 90 psig (Bradley, 2004). The water passes through a pre-treatment system designed, installed, and maintained by Culligan. This treatment system, which has been designed to meet flow rate requirements for both of the TITAN^{TM} EC-750 electrolyzers, consists of one water softener, one 1,240 carbon exchange filter bed, three mixed-bed deionizers, and a resin trap (Wells, 2004).

Water flows first through a manual shut-off valve, then to the softener that both softens the water and filters larger constituents through a 10 micron filter. The softener is followed by the carbon filter and subsequently the DI beds, which comprise the bulk of the treatment system. The resin trap completes the treatment by reclaiming resin residuals from the DI tanks. At a maximum flow rate of 5 gpm and 200k ohm-cm resistivity, the out-flowing water exceeds Type II ASTM standards and the requirements for the electrolyzers (Wells, 2004).

Quality control meters are installed after each DI bed to ensure proper treatment and a Thornton resistivity meter checks water quality before distribution to the electrolyzers. An automatic shut-of valve controls the flow of passable and non-passable water. The maximum demand flow rate for this system is 528 gallons per day with a minimum resistivity of 100k ohm-cm. The plumbing for the system is ¾ in., schedule 80 PVC throughout (Wells, 2004).

1.8 Venting and Plumbing

The plumbing system for the station is divided into four sections: Feed Water, Oxygen, Low Pressure Hydrogen and High Pressure Hydrogen. The basic schematics of the plumbing system are detailed in **Appendix B** and **Appendix C**. All plumbing to be used in the facility meets ASTM standards.

1.8.1 Feed Water Plumbing

The purified feed water is supplied to the electrolyzers through ¾ in. stainless steel pipes. A check valve is included in the line to prevent back-flow of purified water.

1.8.2 Oxygen Plumbing

Oxygen produced during electrolysis is vented to the atmosphere. During normal operating conditions, 21 Nm^3/hr of oxygen is produced by each of the two electrolyzers. The oxygen vent will be located separately, at least 15 ft away from both the high and low-pressure hydrogen vents.

1.8.3 Low Pressure Hydrogen Plumbing

All of the plumbing for hydrogen distribution will consist of stainless steel tubing and piping meeting ASTM A269 standards. As previously stated, each electrolyzer produces 42 Nm^3/hr of hydrogen at 115 psig during normal operation. For safety reasons, a hydrogen vent line is provided from each electrolyzer. The electrolyzers will have built-in differential pressure regulators to regulate any hydrogen venting. The regulators will ensure that a uniform pressure difference is maintained between the hydrogen and oxygen systems. This protects the internal electrolyzer membranes from untimely damage (Zoellick, 2004). Eight (8) ballast tanks are included in-line between the electrolyzers and the compressors, as described in **Section 1.4**. A forward pressure regulator is located directly upstream from each compressor. The forward pressure regulator ensures that the compressor's inlet pressure requirements are met.

1.8.4 High Pressure Hydrogen Plumbing

Each compressor will deliver hydrogen at 6,000 psig. The maximum outside pipe diameter specified for this pressure is 1 in. (ASME B31.3). A small sample of the hydrogen stream exiting each compressor is analyzed by a trace oxygen analyzer. The high pressure hydrogen is piped to a six cylinder storage system. Tank storage is controlled by a programmable logic controller (PLC) through solenoid valves at the inlet and outlet of each cylinder. The control system is described in detail in **Section 1.9**.

1.8.5 Plumbing Safety

The plumbing system is designed with considerable attention to safety. The hydrogen piping is sized to satisfy maximum allowable working pressure (MAWP) limitations. The major pipes used are shown in **Table 2**. The connections and fittings are manufactured by Swagelok and are designed specifically for light gases so as to greatly minimize any leaks. Pressure relief devices (PRDs) are placed in-line with every regulator and are set to trip if the regulator fails. Each storage tank is also equipped with a PRD which is set to trip at a value slightly below the maximum holding pressure of the tank. Pressure switches send a signal to shut down the system if any PRD trips.

Although not likely, there is a risk that air could enter the hydrogen stream. After compression, if oxygen continues to exist in the hydrogen stream at a high pressure an unstable and possibly explosive mixture will result. To monitor this situation, a trace oxygen analyzer will continuously sample the hydrogen stream exiting the compressor. The analyzer will be specified to send a shut down signal to the PLC if the amount of oxygen in the hydrogen stream reaches 50% of the lower explosive limit (4% oxygen by volume).

Table 2- Pipe specifications for each plumbing sub-system.

	Pipe Outside Diameter (inches)	Pipe Material
Oxygen	1	Stainless Steel Schedule 40
Low Pressure Hydrogen	2	Stainless Steel Schedule 40
High Pressure Hydrogen	1	Stainless Steel Schedule 160

1.9 Controls and Instrumentation

The control system that operates the generation and distribution systems of the *H_2-Go!* fueling station can be classified according to three major areas:

1. The Electrolyzer and Compressor
2. Storage and Dispensing
3. Safety

A system power distribution panel (PDP) will accept 3-phase power from the grid and distribute the power throughout the system. This PDP will also house the main electrical fuses and a manual switch for the system. A monitor and annunciation control panel uses a central programmable logic controller (PLC) that monitors and controls system operation. This panel also houses a manual shut off switch for the system. Both panels are located in a control room isolated from the industrial shed to comply with NEC regulations.

1.9.1 The Electrolyzer and Compressor

Pressure switches located in-line will automatically operate the two electrolyzers and compressors. During normal operation the electrolyzer's output pressure and flow rate will be matched to the compressor's input requirements.

The line downstream of the compressor is connected to each storage cylinder in parallel. Whenever the pressure in this line drops below 5,990 psig, the downstream pressure switch turns the compressor on. The set point of the pressure switch will be set at 10 psig below the outlet pressure of the compressor to ensure that minor pressure fluctuations in the pipe do not turn the compressor on and off. When the pressure downstream reaches 6,000 psig, the pressure switch turns the compressor off. In addition, the compressor is equipped with a gas control panel that includes a pressure regulator, gauge and a switch that operates based on upstream suction pressure. This ensures that the compressor will run only when the suction pressure is above the set point.

The electrolyzers will be operated in a similar fashion. The internal pressure switch turns them on when the downstream pressure drops to 110 psig (5 psig below specified output pressure). When the compressor turns on, it draws hydrogen from upstream, causing the pressure to fall. As soon as this pressure reaches 110 psig, the electrolyzers are engaged. When the pressure reaches 115 psig, the pressure switch turns off the electrolyzer. This simple control system ensures smooth, on-demand production of hydrogen.

A ballast tank in line between the compressor and the electrolyzer serves two important functions. Due to the high flow rate of the system, a time lag caused by the delayed response of the pressure switches and the electrolyzer may result in a rapid pressure drop. If compressor suction pressure drops below the set point the compressor will shut down. In addition the ballast tank serves to buffer the hydrogen line to prevent compressor shut down. There may be times when the electrolyzer is operating at less than the full power. To ensure that the compressor's normal inlet flow rate requirements are met, the ballast tanks will supplement the electrolyzer's hydrogen generation during these occasions.

1.9.2 Storage and Dispensing

In an effort to optimize compressor efficiencies and get the most work from the pressure energy stored in each of the six storage tanks, the station will use a cascade dispensing system. This system allows the hydrogen storage tanks to discharge according to a "pressure matching" algorithm. The descriptions of the algorithms used for programming the PLC are provided in **Section 1.9.2.1** and **1.9.2.2**.

1.9.2.1 Discharge Algorithm

An algorithm has been written to program the PLC to discharge the storage tanks throughout the normal operating day. The pressure sensors on the downstream side of the storage tanks signal pressure changes that cause the solenoid valves to open and close to match vehicle pressure. This algorithm is shown graphically in **Appendix D**.

1.9.2.2 Recharge Algorithm

An algorithm has been written to program the PLC to control the pressures in the storage tanks during recharge. This algorithm initiates as soon as the electrolyzer comes online and continues to run until all tank pressures reach 6,000 psig or the electrolyzer goes offline. This algorithm is shown graphically in **Appendix E**.

1.9.3 Safety

The *H_2-Go!* Station is protected against several possible safety hazards. Each of these hazards will be detected by an electronic instrument that sends a signal to the central PLC. The central PLC will process all signals and shut down the entire system if monitored parameters stray outside allowable limits. The annunciator, a display panel, displays the status of each monitored parameter and equipment. The annunciator can also sound an alarm if necessary. The table below outlines each hazard and detecting instrument. Safety issues are discussed in detail in **Section 2**.

Table 3- Safety Instrumentation in Station Control.

Safety Hazard	Detection Method
Hydrogen leak	7 Hydrogen sensors located strategically around the facility
Hydrogen fire	2 UVIR self-checking flame detectors - 1 in the industrial shed, 1 near the dispenser
Oxygen in high pressure hydrogen storage	Trace oxygen analyzer located just downstream of the compressor
Fire unrelated to the hydrogen system	Up to 5 fire alarms with analog output located around the facility
Pressure issues or failures in plumbing and hydrogen storage cylinders	Pressure switches in line with pressure relief devices wired to the central PLC

1.10 System Electricity Demands

On-site electrolysis for the production of hydrogen demands a large amount of electricity due to the demand load of the electrolyzer units. In total, the electrolyzers alone are expected to consume 3,650,000 kilowatt hours in one year (See **Table 5)**. The electrolyzer's electrical load is about 5 times that of the hydrogen compressor. The control system for the gas generator units requires instrument quality air (IQA) supplied by a Kaeser model SX-6 air compressor. Then this unit consumes roughly one eighth of the hydrogen compressor's load. This air compressor is oversized to supply compressed air for tire inflation purposes at the station. Mini-mart usage is predicted to be 162,500 kWh/yr (Marrufoo, 2004).

Table 4- Energy use of the fueling station.

Components	kWh/year
Electrolyzer	3,650,000
H_2 Compressor	86,870
IQA Supply	28,944

2 Safety Analysis

2.1 Safety in Station Design

The use of hydrogen as a fuel is fairly limited and hence is viewed with suspicion and distrust by the public at large. Unfortunately, the famous Hindenburg disaster is in most cases a person's strongest image of hydrogen fuel. The *H_2-Go!* fueling station will be among the first generation of hydrogen fueling stations in the world. Any major safety failure is likely to gain a high profile and would be a major setback for hydrogen as a motor vehicle fuel for the future. Hence every aspect of the station will be designed with safety as paramount concern.

Several national agencies are in the process of developing safety codes and standards for hydrogen refueling stations and its use in motor vehicles (NHA 2004). Currently, however, no codes and standards exist specifically for hydrogen fueling stations. Existing standards and codes applicable to hydrogen fueling stations, including NFPA 50A "Standards for gaseous hydrogen systems at consumer sites", will be closely followed in the design of the *H_2-Go!* station. Since it processes more than 15,000 scf of hydrogen, the *H_2-Go!* station is classified as Type 3 by NFPA 50A. The following designs were dictated by this classification:

- The electrolyzers and compressors are housed in a separate industrial shed with ventilation for low pressure hydrogen, high pressure hydrogen and oxygen. Each wall of the shed will be at least 5 feet from electrolyzer (**Figure 11, Appendix G**).
- All equipment in the industrial shed meets Class 1, Division 2 standards as specified in Article 501 of NFPA 70A.
- All equipment within 15 ft of the dispenser meets Class 1, Division 2 standards as specified in Article 501 of NFPA 70A.
- The storage tanks are located outdoors and are protected on two sides by a high chain-link fence and by fire-resistant walls on the other two sides. The tanks are sheltered from the weather. The storage area is labeled "HYDROGEN – FLAMMABLE GAS – NO SMOKING – NO OPEN FLAMES". Each storage cylinder is labeled "HYDROGEN". (NFPA 50A, 1994)
- All the hydrogen piping and fittings conform to ASME B31.3 standards.
- The power distribution panel and the control panel which are made for unclassified locations are housed in a separate room and not in the industrial shed. (Bortel, 2004)
- In accordance with CGA S standards all high pressure piping and storage are fitted with PRDs.
- A central PLC monitors all the station's important parameters and automatically shuts down the generation system if any of these parameters stray outside their safety limits. An annunciator indicates the location of the fault. The safeties built into the control system are explained in more detail in **Section 1.9**.
- All technical personnel will be trained in hydrogen safety and fuel station operating procedures. Refresher courses will be conducted annually.
- All other standard safety requirements that apply to CNG refueling stations are also followed. (NFPA 52, 1998)
- Site layout and clearance distances between the hydrogen system and other areas of site will meet all NFPA 50A requirements.

2.1.1 Eleven Major Modes of Safety Failure

Even when safety regulations are scrupulously followed in the construction and regular operation of the station, extraordinary hazards may still occur. In order to prepare for these contingencies, the top eleven safety failures with respect to severity of damage were identified. The three most probable of these events were identified and mitigation measures developed. The eleven major failure modes ranked according to probability of occurrence are:

1. A vehicle crashing into the fuel dispenser.
2. Fire unrelated to the hydrogen system that endangers the hydrogen system.
3. Pipe rupture, cylinder rupture or component failure in the high pressure hydrogen system.
4. Vehicle drives away with refueling hose attached.
5. A hydrogen fire in the vent stack of the industrial shed.
6. An earthquake or other natural disaster.
7. A potassium hydroxide spill from the electrolyzer.
8. A hydrogen leak that results in a fire or explosion.
9. A vehicle, most likely a supply truck, crashing into the hydrogen storage or industrial shed.
10. Oxygen in hydrogen storage causing a high pressure explosive mixture.
11. A terrorist attack on the facility.

2.1.2 Highest Probability Safety Failure - Vehicle crashing into fuel dispenser

The area around the dispenser will see the most vehicular activity. The sheer volume of traffic makes a vehicle – dispenser collision the most likely safety hazard. The hazard involved in such an incident will increase greatly if it results in the rupture of a high pressure hydrogen line. The first line of defense would be to minimize the probability of the rupture of a high pressure line. The dispenser island is protected by bollards that will prevent any damage to the dispenser if struck in the direction of traffic flow unless the collision happens at high speed (**Appendix F**). The dispenser is more vulnerable if struck perpendicular to the direction of traffic flow. However, even at this angle of attack the damage will be greatly reduced because the dispenser is placed on a slightly elevated island and is made of strong steel. Hence, unless the impact is fairly strong and front-on, the rupture of a high pressure hydrogen line is extremely unlikely.

If the hydrogen line does rupture at the dispenser, steps can be taken to stem hydrogen flow while simultaneously minimizing the chance of ignition. A 400 ft^2 area around the dispenser is designated as smoke free and is strictly enforced by the operator. Also, any electrical equipment located in this area (e.g. overhead lighting) will meet Class 1, Div. 2 hazardous location requirements. This forces any possible ignition source to originate from the collision itself. To shut off hydrogen flow as soon as possible, the PLC logic will close the solenoid valves at the cylinders if the integrity of the pressure transducer at the dispenser is lost. It will also shut down the generation system. In addition, manual system shut down switches are located at several locations around the station, any of which can be tripped to close the solenoid valves and shut down the generation system.

Since the dispenser is located outdoors, the ventilation is excellent and the hydrogen release will disperse quickly (**Figure 9, Appendix F**). All of the above factors, coupled with hydrogen's extremely low viscosity, make the possibility of a fire or explosion very unlikely. The station is well equipped with fire fighting capabilities and a hotline 911 link. The most likely outcome of a high pressure rupture is flying shrapnel and high velocity directed gas flow.

2.1.3 Second Highest Probability Safety Failure – Fire unrelated to the hydrogen system

With the design of the hydrogen system exhaustively accounting for safety issues, a hydrogen fire is far less likely to occur than a normal building fire. The utility shed is a special building with all equipment in compliance with Class I, Division 2 NEC standards (NFPA 70A, 2002). The hydrogen plumbing material is high grade stainless steel which can withstand high temperatures (Swagelok, 2004). The hydrogen storage cylinders are made of seamless carbon steel that can also withstand high temperatures. The storage area is equipped with sprinklers that are triggered by heat sensors. Every cylinder is equipped with a vent valve. If there is enough forewarning, the tanks can be manually vented. The walls bordering the mini-mart are fire resistant, which should give enough time for manual venting of storage tanks and system shut down. Manual valves are provided throughout the system to allow for venting of different sections if needed. Heat sensors are located strategically around the facility that will send a signal to the control system for shut down. Overall, the station is well equipped with fire fighting equipment and a 911 hotline link.

Firefighting equipment can be brought in and the hydrogen tanks can be showered with water to keep them cool in the event of a facility fire. PRDs are likely to vent the cylinder contents if the pressure rises too high due to heating from fire, thereby preventing tank rupture.

2.1.4 Third Highest Probability Failure – Failure in the high pressure hydrogen system

The hydrogen plumbing was designed in close compliance with ASTM B31.3 standards for maximum allowable working pressures (MAWP) for all the piping. The high pressure hydrogen system is carefully plumbed to incorporate PRDs which will trip in the event of the failure of any component like pressure regulators, valves and pressure switches (**Appendix C**). All of the pressure relief devices are set 10 percent below the maximum allowable working pressure (CGAS, 1995) or other relevant working pressures. In addition, most of the high pressure piping is contained in restricted access areas between the industrial shed and the gas storage. Only one high pressure line enters the public access area. All tanks are fitted with PRDs that prevent any bursting. Hence, rupture of high pressure lines is an extremely unlikely event. Due to its low viscosity, hydrogen rarely creates static sparking, thereby reducing chances of ignition in the event of a rupture.

The greater danger in the event of high pressure accidents is flying shrapnel and high velocity gases. Personnel in the industrial shed are required to wear eye and ear protection and laboratory overalls. The walls of the industrial shed and the two walls of the storage area are reinforced concrete and will prevent any penetration by flying objects (**Figure 9, Appendix F**). However, it is not possible to enforce protective gear in the public access area and hence, the one high pressure line in that zone will be enclosed in a reinforced tube.

2.1.5 Other Possible Safety Failures

2.1.5.1 Vehicle drives away with refueling hose attached

Since hydrogen fueling stations are nascent, self-service is not permitted. Refueling is performed by a trained operator. The likelihood of this accident is low, however, the central PLC will close the cylinders' solenoid valves and shut down the system if the pressure transducer in the hose loses its integrity. Break-away hoses with automatic shut-off are specified for the pump. In the unlikely event that the released hydrogen does ignite, the flame will not spread to the tanks and can be contained easily.

2.1.5.2 A hydrogen fire in the vent stack of the industrial shed

The Hydrogen vent stack is the most likely place for a hydrogen fire. The stack is equipped with a self-checking UVIR flame detector and helium. The flame detector can open the solenoid valve to douse the stack in helium if it detects a fire (**Figure 9, Appendix F**).

2.1.5.3 An earthquake or other natural disaster

Arcata is located close to the Mendocino triple junction and is one of the most seismically active areas in the world. Rigid plumbing connections between components have strain relief features that allow relative movement between components without rupture. The building codes in this region deal extensively with earthquake issues and those will be followed for all structures at the *H_2-Go!* facility. The electrolyzers, compressors and storage tanks are anchored tightly in place.

2.1.5.4 A potassium hydroxide spill from the electrolyzer

The Teledyne EC-750 has a well built potassium hydroxide and water circulation system. Only trained personnel will service the electrolyzer and will be required to wear gloves, overalls and eye protection. Dry sand bags will be stocked on-site to soak up any spill. The spill will be contained within the industrial shed in most cases. All personnel will be trained in hazardous spill response procedures.

2.1.5.5 A hydrogen leak that results in a fire or explosion

Preventive and contingency measures have already been discussed for hydrogen fires. Self-checking flame sensors are located strategically around the facility that will immediately shut down the system if there is a hydrogen fire. That would probably cut off fuel for the fire in most circumstances. However, if this unlikely event does occur, it is a serious hazard and alarms will be sounded and the premises will be evacuated immediately. The hydrogen storage should be vented if it can be done safely. If this is not possible, and the storage area does catch fire, an explosion is still unlikely to occur. The tanks will be sprayed with water to keep them cool and the PRD will vent hydrogen to prevent rupture of the tanks. Even if the tanks do rupture, air will not enter them since they are at high pressure, eliminating the possibility of a high pressure explosion.

2.1.5.6 A vehicle crashing into the hydrogen storage or industrial shed

A vehicle crashing into the storage shed is unlikely to collide with the electrolyzer or the compressor since they are placed at a substantial distance from the wall. The walls themselves are reinforced and extremely strong. The storage area is protected by a strong chain link fence on two sides and reinforced concrete walls on the other two sides (**Figure 9, Appendix F; Figure 11, Appendix G**). Further, the tanks themselves are made of seamless carbon steel built to withstand 7,000 psig of pressure. If in the extremely unlikely event that such a crash causes a high pressure rupture, refer to **Section 2.1.4** for information on measures and consequences.

2.1.5.7 Oxygen in hydrogen storage causing a high pressure explosive storage volume

There have been occasions when the hydrogen produced by an electrolyzer has been contaminated with oxygen due to a crossover from anode to cathode. Further, ambient air can also enter the hydrogen plumbing if there is a fracture and the pressure in the line falls below atmospheric pressure. The danger from such a mixture increases by several orders of magnitude if it is sent into compressed storage. The TITAN™ EC-750 uses a membrane to separate the anode from the cathode and also pressurizes the hydrogen side well above the oxygen side (Bortel, 2004). Therefore, if any cross-leak does occur, hydrogen will enter the oxygen stream and not vice versa. The oxygen is immediately vented. The rest of the hydrogen plumbing holds hydrogen pressurized at 115 psig. Even in idle mode, the electrolyzer ensures that the plumbing is maintained at pressure. Hence, any fractures in the plumbing will not result in the suction of air into the hydrogen line. In addition, the compressor will shut down if the suction pressure drops too low.

Although the event is extremely unlikely, if the high pressure storage does contain an explosive mixture, the consequences are potentially disastrous. Therefore, as a last and definite check that no explosive mixture is sent into storage, a trace oxygen analyzer continuously samples the stream exiting the compressor. If it detects oxygen at or above 50% of the lower explosive limit, the system is immediately shut down. These several checks for oxygen in the hydrogen stream make it an event that is very unlikely to occur. If such an event did occur, tanks would be transported to a safe, remote location and safely vented in a controlled manner.

2.1.5.8 A terrorist attack on the facility

Arcata, California is an isolated small town dominated by a peaceful student population and known for its low crime rate. San Francisco is six hours to the south and Portland is eight hours to the north by road. All of these factors make Arcata a seriously unlikely place for a terrorist attack. However, in the event that one occurs, the civilian casualties are likely to be low since our station is located in a sparse industrial zone.

2.2 Safety System Components

2.2.1.1 Plumbing Safety

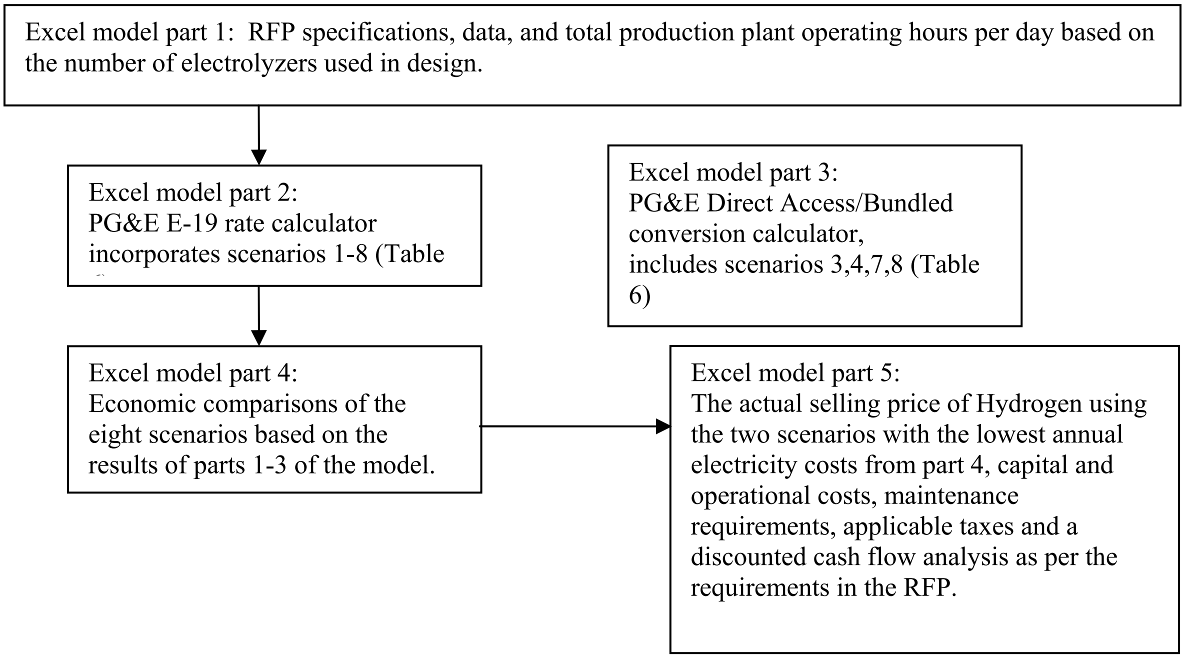
The plumbing system is also designed with safety in mind. The hydrogen piping is sized to satisfy maximum allowable working pressure (MAWP) limitations. The major pipes used are shown in **Table 5**. The connections and fittings, manufactured by Swagelok, are designed specifically for light gases such as hydrogen to minimize leaks. Pressure relief devices (PRDs) are placed inline after every regulator and are set to trip from the regulator failure. Each storage tank is also equipped with a PRD which is set to trip at a value slightly below the maximum holding pressure of the tanks. Pressure switches send a signal to shut down the system if any PRD trips.

Table 5- Pipe Specifications for each plumbing sub-system

	Pipe Outside Diameter (inches)	Pipe Material
Oxygen	1	Stainless Steel Schedule 40
Low Pressure Hydrogen	2	Stainless Steel Schedule 40
High Pressure Hydrogen	1	Stainless Steel Schedule 160

3 Economic Analysis

The economics inherent in hydrogen production are dependent on the manufacturing components chosen, their energy usage, and the ongoing maintenance and operation schedules for that equipment. In particular, the cost of hydrogen production using electrolysis is highly dependent upon electric utility rates. Since these utility rates are variable based on time of use, it is possible for a larger production plant to be more profitable over time despite the larger initial capital cost. A Microsoft Excel model was created for the purpose of comparing the effects of plant size variation with economic benefits. Ivan Marrufoo, Senior Major Account Manager for Pacific Gas and Electric (PG&E), furnished an E-19 rate calculation spreadsheet and a Direct Access rate calculation spreadsheet which were incorporated into the Excel model and used to compare eight scenarios (**Table 6**). **Figure 2** portrays the flow of the computations used in the model. Due to the size of the model only a representative sample is included in **Appendix I**.



Excel model part 1: RFP specifications, data, and total production plant operating hours per day based on the number of electrolyzers used in design.

Excel model part 2:
PG&E E-19 rate calculator
incorporates scenarios 1-8 (Table

Excel model part 3:
PG&E Direct Access/Bundled conversion calculator,
includes scenarios 3,4,7,8 (Table 6)

Excel model part 4:
Economic comparisons of the eight scenarios based on the results of parts 1-3 of the model.

Excel model part 5:
The actual selling price of Hydrogen using the two scenarios with the lowest annual electricity costs from part 4, capital and operational costs, maintenance requirements, applicable taxes and a discounted cash flow analysis as per the requirements in the RFP.

Figure 2- A flow chart of the Excel model used to determine the scenario that minimizes annual electricity costs.

Table 6- Comparative economic results of the eight scenarios modeled

Expense Category	2 Electrolyzers				3 Electrolyzers			
	Time Of Use rates without solar	Time Of Use rates with solar	Fairhaven continuous Direct Access	Fairhaven non-continuous Direct Access	Time Of Use rates without solar	Time Of Use rates with solar	Fairhaven continuous Direct Access	Fairhaven non-continuous Direct Access
Scenario #	1	2	3	4	5	6	7	8
Capital Costs	$880,000	$1,780,000	$880,000	$880,000	$1,320,000	$2,220,000	$1,320,000	$1,320,000
Annual Electricity Costs	$541,099.03	$526,968.60	$351,487.02	$469,514.15	$488,108.12	$471,657.58	$362,286.14	$470,662.62

As can be seen in **Table 6**, the use of three electrolyzers can result in an economic gain by allowing for production to occur during off-peak hours. The effects of using a 100kW photo-voltaic array to off set utility costs were evaluated. Using a photovoltaic array in a three unit system would allow the station to sell back solar generated electricity at peak power rates. Ultimately the analysis revealed that the photovoltaic options were not cost effective due to high capital costs and low annual daily full sun hour averages in Arcata. The electrical costs associated with **Scenarios 1**, **2**, **5**, and **6** in **Table 6** reflect an additional $0.013 / kWh included for the purchase of certified Green-e tags. Green-e tags effectively procure the environmental benefits associated with renewable energy, for all kilowatt hours for which tags are purchased (Nye, 2004). In this way the grid power consumed by the station under **Scenarios 1**, **2**, **5** and **6** can be considered to be "green" by nationally accepted standards.

The Direct Access arrangement reflected in **Scenarios 3**, **4**, **7** and **8** in **Table 6** is based on a contract arrangement with Fairhaven Power Plant on the Samoa peninsula in Eureka. This arrangement is based on a bulk rate of $.064784/ kWh which reflects the current arrangement between PG&E and Fairhaven Power Plant (Marino, 2004). The Fairhaven Power Plant produces 16MW of electric power by burning waste from the forest products industry, which would otherwise be deposited in the landfill. Under the Direct Access scenario the station enters into a contract agreement with Fairhaven Power Plant under which all electric power for the station is procured. The station also enters into a contract with PG&E for transmission and distribution services based on an E-19 primary rate. The E-19 rate is designated for customers whose peak demand is between 500 and 999 kW. The guidelines of the E-19 *primary* rate structure dictate that customers supply their own transformer. The alternative showing the minimum annual electricity cost, **Scenario 3**, is used to generate the final selling price of hydrogen presented in this analysis.

The state of Direct Access contracts in California is currently undergoing review by the California Public Utility Commission (Marrufoo, 2004). Potential changes introduce an element of uncertainty into the price per kWh that would be formalized in any future contract with Fairhaven Power Plant. Furthermore, since this station is designed for ease of replication, and not all potential sites will have a Direct Access option, an analysis using **Scenario 1** (**Table 6**) is presented. These two scenarios represent the upper and lower bounds of the selling price and exemplify station design flexibility.

3.1 Capital costs for equipment and structures

All capital costs associated with the station are listed in **Table 7**.

Table 7- Listing of all capital costs.

Hydrogen System				
Item	**Quantity**	**unit cost**	**Total**	**References**
Manual 2-way valve	25	$67.00	$1,675.00	Oakland Valve and Fitting (Kole, 2004)
Forward Press. Regula	Supplied with compressor			TBE (Bortel 2004)
Press. Relief	19	$110.00	$2,090.00	Oakland Valve and Fitting (Kole, 2004)
Check Valve	1	$40.00	$40.00	Oakland Valve and Fitting (Kole, 2004)
Pressure Gauge	11	$75.00	$825.00	Oakland Valve and Fitting (Kole, 2004)
Pressure Switch	9	$182.00	$1,638.00	Oakland Valve and Fitting (Kole, 2004)

Control System

Item	Quantity	Unit Cost	Total	Reference
H2 sensors	7	$550.00	$3,850.00	RKI instruments (Holcum, 2004)
O2 in H2 sensor	2	$5,400.00	$10,800.00	Zoellick, 2004
H2 flame detector	2	$2,000.00	$4,000.00	Spectrex inc. (Johnson, 2004)
Electrical Circuit Enclo	1	$401.00	$401.00	Hoffman enclosures inc. 2004
Annunciator	1	$255.00	$255.00	Ametek inc. (Vangelas, 2004)
Switches and others	1	$300.00	$300.00	Zoellick, 2004
Programming labor	1	$4,000.00	$4,000.00	Rommel, 2004
pressure switches	9	$182.00	$1,638.00	Zoellick, 2004
Central PLC	1	$3,000.00	$3,000.00	Rommel, 2004
Solenoid valves	12	$600.00	$7,200.00	Zoellick, 2004
Pressure transducers	7	$450.00	$3,150.00	Zoellick, 2004
Hygrometer	2	$349.00	$698.00	Newport Electronics 2004
		20% overhead	$4,721.20	
		Total	**$44,013.20**	

Water System

Item	Quantity	Unit Cost	Total	Reference
Manual 2-way valve	2	$10.00	$20.00	Oakland Valve and Fitting (Kole, 2004)
Check Valve	1	$70.00	$70.00	Oakland Valve and Fitting (Kole, 2004)
Piping	1	$20.00	$20.00	Oakland Valve and Fitting (Kole, 2004)

Piping/Tubing

Item	Length	Cost/length	Total	References
O2 1" OD,0.065" WT	30	$10.50	$315.00	Oakland Valve and Fitting (Kole, 2004)
H2 2" OD, Sched 40	40	$28.20	$1,128.00	Oakland Valve and Fitting (Kole, 2004)
H2 1" OD pipe 160S	100	$35.80	$3,580.00	Oakland Valve and Fitting (Kole, 2004)
		20% overhead	**$19,885.48**	
		Total	**$31,286.48**	

Capital Costs

Item	Quantity	$ / unit	Total	References
Brown Field Purchase	1	35,000.00	35,000.00	(Conlon 2004)
Equipment shed /sq. f	650	65.00	42,250.00	Beacom Construction (Morris 2004)
Mini-mart /sq. ft.	800	112.00	89,600.00	Beacom Construction (Morris 2004)
Awning /sq. ft.	400	18.00	7,200.00	Beacom Construction (Morris 2004)
Asphalt /sq. ft.	3550	1.75	6,212.50	Beacom Construction (Morris 2004)
Fencing /linear ft.	120	13.00	1,560.00	Beacom Construction (Morris 2004)
Bollards	2	200.00	400.00	Beacom Construction (Morris 2004)
Water filtration system	1	1,325.00	1,325.00	Culligan Water (Wells 2004)
Compressor	2	131,000.00	262,000.00	TBE (Bortel 2004)
High pressure H2 tank	6	28,333.00	170,000.00	(Pratt 2004)
Dispenser	1	48,600.00	48,600.00	Fueling Technologies Inc. Zubin
Electrolyzer Unit + Ove	2	440,000.00	880,000.00	TBE (Bortel 2004)
Instrument quality air c	1	5,500.00	5,500.00	Kaeser Compressors (Knight 2004)
Transformer and servi	1	79,000.00	79,000.00	Kneaper Electric (Kneaper 2004)
Miscellaneous capital c	N/A	25,000.00	25,000.00	Estimate
Cost of Incorporation		100.00	100.00	www.ssca.gov 2/26/04
		TOTAL	**$1,729,047**	

3.2 Operating costs and maintenance requirements

Tables 8 and **9** represent the operational and maintenance costs calculated for the station design.

Table 8- Operating and continual costs

OPERATING COSTS				
Water				**References**
Mini mart usage (1397 ft^3/mo)				Fuelstar gas (Mahmood, 2004)
Electrolyzer usage (1984 ft^3/mo)				Fuelstar gas (Mahmood, 2004)
Total per month (3381 ft^3/mo)				Fuelstar gas (Mahmood, 2004)
	Units	**$/unit**	**$/year**	
Water	base fee	$3.25	$39.00	
	per 100ft^3 <2500 ft^3	$1.75	$525.00	Arcata Water District (Bradley, 2004)
	per 100ft^3 >2500 ft^3	$1.60	$169.15	Arcata Water District (Bradley, 2004)
Total water use			**$694.15**	
Waste				
Mini mart waste (1397 ft^3/mo)				
Waste	per first 450 ft^3	$13.75	$165.00	Arcata Water District (Bradley, 2004)
	per 100ft^3 after 450 ft^3	$1.62	$184.10	Arcata Water District (Bradley, 2004)
Total Waste			**$349.10**	
Utility user's tax		3%	$31.30	Arcata Water District (Bradley, 2004)
Monthly capital hook up fee		$5.00	$60	Arcata Water District (Bradley, 2004)
Electricity and gas				
Electricity	$/kWh Variable See Appendix		**$351,487.02**	PG&E (Marrufoo, 2004)
Natural gas	$/month ($300winter-$2summer)		**$1,216.00**	Fuelstar gas (Mahmood, 2004)
TOTAL			**$353,837.56**	
CONTINUAL COSTS				
DI water filters	First year setup	$3,580.00	$3,580.00	Culligan Water (Wells, 2004)
DI water filters all other years	nine year supply	$3,680.00	$3,680.00	Culligan Water (Wells, 2004)
Nitrogen	$/scf	$0.118	$38	Eureka Oxygen Supply (Collins, 2004)
TOTAL			**$7,297.76**	
Taxes				
Property Tax $/Year	1% of full cash value		$1,668.50	Acctg. Dept, HSU (Kenyon, 2004)
excise tax $/gallon	$0.32/gallon		$17,520.00	Fuelstar gas (Mahmood, 2004)
unemployment tax $/year	3.4% up to $7000/ employee/ year eg.$238/empl/y		$714.00	CA St. EDD (Johnson, 2004)
worker's comp $/year	$10.15/$100 of employee salary		$9,135.00	IRB (Clarkson, 2004)
Employment training tax $/yr	.10% of up to $7000 yearly eg. $7/yr		$7	CA St. EDD (Johnson, 2004)
TOTAL			**$29,044.50**	
		Labor	**3**	Note: includes benefit package
Salary	$/year	$30,000	$30,000	Professional Judgement
Total labor cost			**$90,000**	
Insurance				
Comprehensive business package including liability and property	$/year	$10,000	$10,000	Fuelstar gas (Mahmood, 2004)
Business Liscence	($40/yr + $10 for each employee)	$70	$70	Arcata City Hall , 2004
Advertising				
media pkg (one time fee)	$	$4,275	$4,275	C.R. and Co. (Anderholm, 2004)
Billboard /month	$/month for two billboards	$3,000	$18,000	C.R. and Co. (Anderholm, 2004)
pamphlets 100	$/pamphlet	$1.12	$112.00	Zoellick, 2004
sineage /5	one time cost	$2,734	$2,734	Zoellick, 2004
TOTAL (per year)			**$25,121**	
GRAND TOTAL			**$515,370.82**	

Table 9- Maintenance type and labor requirements

Compressor + Ballast tank	Hours/year	References
Inlet filter	2.5	TES (Bortel, 2004)
Lubrication system	2.5	TES (Bortel, 2004)
Process check valves	1.5	TES (Bortel, 2004)
Oil inlet check valves	0.5	TES (Bortel, 2004)
Hydraulic Oil relief vlave	0.5	TES (Bortel, 2004)
Miscellaneous maintenance		
Dispensor service	6	SERC (Gopal 2004)
Storage tank inspections	12	SERC (Gopal 2004)
Process control checks	4	SERC (Gopal 2004)

Electrolyzer Unit Titan EC-750	Hours/year	References
Minor Electrolyte Loop Service	16	TES (Bortel, 2004)
Gas Sensor Functional Check	4	TES (Bortel, 2004)
Inspect electrolyte pump internals	4	TES (Bortel, 2004)
Replace coaliscing filter cartridge	1	TES (Bortel, 2004)
Bubble check for gas leaks	1	TES (Bortel, 2004)
Module re-torque	4	TES (Bortel, 2004)
Air pressure regulator adjustment	1	TES (Bortel, 2004)
Electrolyte change	4	TES (Bortel, 2004)
KOH Heat Exchanger Inspection/clean	2	TES (Bortel, 2004)
Inspect air system regulator filters	1	TES (Bortel, 2004)
Inspect and clean gas condenser tubes	2	TES (Bortel, 2004)
Replace gas sensor molecular sieve	1	TES (Bortel, 2004)
Replace product gas filter	0.5	TES (Bortel, 2004)
Check valve inspection and cleaning	4	TES (Bortel, 2004)
Check valve leak checks	1	TES (Bortel, 2004)
Back pressure regulator adjustment	0.5	TES (Bortel, 2004)
Instrument air pressure switch check	0.5	TES (Bortel, 2004)
Clean and inspect power supply internals	1	TES (Bortel, 2004)
Solenoid valve inspection and cleaning	4	TES (Bortel, 2004)
Inspect/ clean trap orifices 375 and 475	0.5	TES (Bortel, 2004)

Items displayed in **Tables 8** and **9** are to be performed by trained, salaried station operators using manufacturer specified maintenance procedures. Labor costs have been included as a part of station operator salary (**Table 8**).

3.3 Selling price of Hydrogen

Yearly cash flow values for the station are projected to be the total annual revenues minus the operating expenses. An estimated 25% profit on $250/day in sales of commodities from the mini-mart adds to the station's revenues from H_2 sales (**Table 10**).

Table 10- Revenues and expenses.

Revenues	
H2 sales $/Kg	$1,136,872.80
Commodities	$22,812.50
TOTAL	$1,159,685.30
Expenses	
Cap cost building	$147,222.50
Cap cost equipment	$1,529,119.40
Capital sum	$1,711,441.90
Operating	$515,403.84
TOTAL	$2,226,845.74

Annual net cash flow for the station is projected to be the cash flow minus the depreciation deductions, multiplied by the tax rates (**Table 11**). Straight-line depreciation and an equipment salvage value of zero is assumed. The return on investment is projected to be 10 years.

Table 11- Estimation of net cash flow

Tax rate		Depreciation rate	
Fed. for Corp.	0.34	Building	0.1
State for Corp	0.0884	Equipment	0.0256

Year	Cash Flow	Deprec Equip	Deprec Bldg	Taxable income	Fed Tax	State Tax	Cash Flow
1	$646,154.08	$147,142.50	$3,774.94	$495,236.64	$168,380.46	$43,778.92	$283,077.26
-	-	-	-	-	-	-	-
10	$646,154.08	$147,142.50	$3,774.94	$495,236.64	$168,380.46	$43,778.92	$283,077.26

The discounted cash flow analysis was calculated using the following model (Willis 2004):

$$-C_o + \sum_{t=1}^{10} \frac{CF}{(1+i)^t} = 0$$

where:

C_o = Capital costs
CF = Net cash flow
i = Internal rate of return
t = Time (years)

By assuming an initial selling price of hydrogen and using Excel solver in an iterative solution routine, the selling price of hydrogen yielding an internal rate of return of 10% has been predicted (**Table 12**).

Table 12: Selling price of hydrogen

Scenario	Selling price of H_2	Internal rate of return
Direct Access with Faihaven Power	$18.57	0.1017
PG&E E-19 rates with Green-e tags	$21.65	0.1007

A predictive $/mile comparison between *H_2-Go!* Inc. hydrogen in an FCV, and gasoline fuel in a conventional vehicle is shown in **Table 13**. This comparison assumes values of $0.058/mile and 27.5 miles per gallon for conventional vehicles, and 60 miles/kgH_2 for FCVs.

Table 13: Dollar per mile comparisons

Energy unit used for comparison	$/mile	Percent Difference from U.S. value	Percent Difference from European Value
H_2 price (Fairhaven Direct Access)	$0.309	81.23%	**45.79%**
H_2 price (PG&E e-19 rate with Green-e tag	$0.361	83.93%	53.57%
Average U.S. gasoline Price	$0.058	N/A	65.38%
Average european gasoline price*	$0.168	**65.38%**	N/A

Footnote: * See table of average European gas prices in Appendix I

Note that the projected $/mile value for hydrogen fuel compares more favorably to the European values than does the U.S. gasoline $/mile value. This observation points to the economic viability of H_2-Go Inc. hydrogen in the global market. This analysis does not attempt to quantify the economic benefits of a CO_2 free transportation system, however, given those benefits, tax incentives and/or subsidies may be deemed appropriate in order to help to catalyze a transition to the hydrogen economy.

4 Environmental Analysis

4.1 Well-To-Tank Carbon Dioxide Emissions

In most cases, the fuel dispensed at a fuel station is not produced on-site. Petroleum based fuels, the most commonly used fuels for automobiles, are mined and refined off-site and are then transported to the station. A well-to-tank (WTT) analysis calculates the total energy used and greenhouse gas (GHG) emissions produced in order to bring a fuel from its origin to the fuel pump. In general, a WTT analysis considers only the operating energy used in various fuel processing steps and not the embodied energy of the capital equipment. A well-to-tank analysis of energy use and greenhouse gas (GHG) emissions can be separated into two levels:

1. The feedstock-related stages analyze the recovery, processing, storage and transportation of feedstocks.
2. The fuel-related stages analyze the production, transportation, storage and distribution of the fuel.

The *H_2-Go!* fueling station generates all of its hydrogen through the electrolysis of water using electricity from the Fairhaven Power Plant which is located near the station (~10 miles West). This plant produces electricity from the waste of the timber industry. The plant is classified as a renewable provider by the U.S. Department of Energy because it generates electricity from woody biomass, continually replenished from the wood waste of the lumber industry (USDOE, 2000). Therefore, although the plant technically emits carbon dioxide to generate electricity, for the purposes of this analysis these emissions can be “written off” or assumed to be zero.

Well-to-tank analyses for regular gasoline have been performed by numerous researchers. The methodology and numbers used in this report are taken from a report produced by the Argonne National Laboratory (ANL) in June 2001 that targets fuel supplies to North America (ANL, 2001). The study used an in-house model to calculate energy use and GHG emissions for various transportation fuels and production pathways. The study included four classes of gasoline, all of which met US EPA Tier 2 vehicle emission standards. The study also looked at hydrogen production from water electrolysis for various grid mixes in the United States. The study statistically accounts for variations in the same production pathway by reporting confidence bounds for all calculated values. For gasoline brought to the pump by existing production pathways and technology, the study calculates that **20,000** grams of GHG are emitted for every million Btu (mmBtu) of gasoline delivered to the tank. From this value and an HHV gasoline energy content of **135,703 Btu/gal** (Larminie et al., 2003), the grams of GHG emissions per gallon of gasoline were computed. Table 14 shows this value along with the grams of GHG emitted per GGE for hydrogen delivered by the *H_2-Go!* station.

Table 14- WTT GHG emissions for gasoline and *H2-Go!* hydrogen.

Standard US Gasoline [(g of GHG)/gal]	2,714
Hydrogen (g of GHG)/gal G.E.	0

4.1.1 Well-to-Wheel Comparison of a Conventional Vehicle and a Fuel Cell Vehicle

The well-to-wheel (WTW) analyses to estimate the GHG emissions savings from the replacement of 50 conventional gasoline cars with 50 FCVs is performed in two parts. The first part looks at the energy used to bring each fuel from its origin to the pump and the energy used to propel the vehicle. The second part looks at the energy used for the entire life cycle by each vehicle type.

To conduct the first part of the study, the following assumptions are made:

- The fuel economy of a conventional gasoline vehicle = ***27.5 mpg of gasoline*** (Rules, 2004)
- The number of miles driven by a vehicle each year is identical to the US National average = ***11,904 miles*** (Energy Information Administration, 2001)

The ANL study conducts a Tank-to-wheel (TTW) analysis for fifteen vehicle architecture/ fuel combinations which are expected to be common in the US market by 2010. The design parameters, including those of the fuel conversion technology, were analyzed in a vehicle simulation model developed by General Motors Inc. The efficiency data obtained from this model was coupled with the WTT data to arrive at Well-to-wheels (WTW) results for over 30 different vehicle-fuel combinations. Since this coupling involves the addition of two statistical distributions, all of the results are presented according to their 20th, 50th and 80th percentile values. **Table 15** shows these results for a conventional standard ignition (SI) gasoline vehicle.

Table 15- GHG emissions for a conventional SI gasoline vehicle (ANL, 2001).

	20th percentile	50th percentile	80th percentile
GHG Emissions (g/gal)	21.04	27.23	28.47

The 50th percentile was used and added to the WTT GHG emissions per gallon of gasoline to obtain the GHG emissions for a conventional gasoline vehicle.

WTW GHG emissions per gallon of gasoline = **2714 + 27.23** = ***2741.23 g of GHG/gal***.

Therefore, the annual GHG emissions for the operation of a conventional gasoline car without accounting for any embodied energy = ***59.8087 metric tons / year***.

The WTW analysis for fuel cell vehicles (FCVs) only needs to account for the life-cycle emissions for the vehicle itself. The fuel provided by the *H_2-Go!* station is GHG free and the FCVs are considered to be zero emission vehicles (ZEVs). Therefore the annual GHG emissions for the operation of an FCV that runs on hydrogen generated at the *H_2-Go!* station = **0 metric tons / year**.

The MIT study titled "On the Road in 2020" performs a life-cycle GHG emissions analysis for different types of vehicles (Weiss, 2000). A life cycle analysis accounts for non-operational GHG emissions for each of the following stages:

1. Vehicle material production
2. Vehicle distribution
3. Vehicle maintenance
4. Vehicle disposal

This analysis excludes vehicle maintenance, as data is very difficult to obtain for these requirements. It is important to note that data on the other three stages is also very difficult to obtain and hence the values in the study are approximates only. In addition, the study assumes a 95% recycling rate for all metal parts, a 50% recycling rate for all plastics and a 300,000 km life for each vehicle. Since these are values projected for 2020, the GHG emission values are a slight underestimate of the present scenario. The two vehicle types relevant to this report were classified as "Current SI Internal Combustion Gasoline" and "Advanced FC Hybrid Hydrogen". The total carbon dioxide emissions in the five life cycle stages for these two vehicle types are shown to be equal in **Table 16**.

Table 16- GHG emissions (g of Carbon per km) in the Five Life Cycle Stages.

Current SI ICE Gasoline Vehicle	4.9
Advanced FC Hybrid Hydrogen Vehicle	4.9

In order to determine the total GHG emissions savings for one year, the GHG emissions from the two parts of the WTW analysis need to be summed for each fuel – vehicle combination. Since the second part is equal for both vehicle types, the difference between the values obtained in the first part is the total GHG emissions saved for one year by replacing 50 conventional gasoline vehicles with 50 FCVs.

Total Annual GHG Emissions saved = *59.8087 metric tons of GHG / year*.

5 Marketing and Education

As a retail distributor of hydrogen and an active business within the community, the responsibilities of the fueling station will include creating a safe and positive image for hydrogen. The successful distribution of hydrogen depends on two main factors: (1) the image of hydrogen as a safe fuel source and (2) a major economic shift away from petroleum based fuels. *H_2-Go!* will assume responsibility not only for the distribution and sale of hydrogen, but also for educating and informing the local community about hydrogen issues. Two categories have been developed to help promote the fueling station: (1) Community Outreach and Education and (2) Marketing and Advertising.

5.1 Community Outreach and Education

Encouraging the community to shift away from petroleum fuel towards a hydrogen economy, and correcting the public misconception of hydrogen as an extremely dangerous substance are both difficult tasks. Community outreach involves focusing on hydrogen education rather than fueling station promotion, thereby making the station available as a public education facility. The promotion of hydrogen and the hydrogen economy will bring about change that will benefit the station both directly and indirectly. Target areas include local grade schools, Humboldt State University, and the public service community.

As older generations have grown up in a petroleum-based economy, and because the transition to a hydrogen-based economy will not occur over night, education and outreach will focus on the younger generation. After all “What greater gift can we offer the republic than to teach and instruct our youth?” -Cicero (James, 2004). *H_2Go!* Inc. will host grade school field trips to the fueling station. These trips to the station will involve a tour of the facilities, including the on-site hydrogen generation facilities and hydrogen education presentations that will be developed for a wide range of age groups.

Humboldt State University (HSU), located in the town of Arcata, is interested in playing an active role in the promotion of a hydrogen economy. James Howard, Dean of The College of Natural Resources and Sciences, stated that HSU’s students “learn about their responsibilities to provide society with better prospects for a healthier, ‘greener’ and more sustainable future” (Humboldt, 2004). A contact has been made with the engineering department of HSU. The Renewable Energy Student Union (RESU), a university club devoted to renewable energy, has developed an interest in having a fueling station in Arcata. Docents, from HSU will assist with or lead the grade school fieldtrips at little or no cost.

Branches of the public service, such as the police and fire departments, and paramedics will need to be trained in appropriate rescue techniques. *H_2-Go!* will offer periodic trainings to public service workers as well as to owners of hydrogen vehicles. The training will outline safety issues, hazards and emergency procedures.

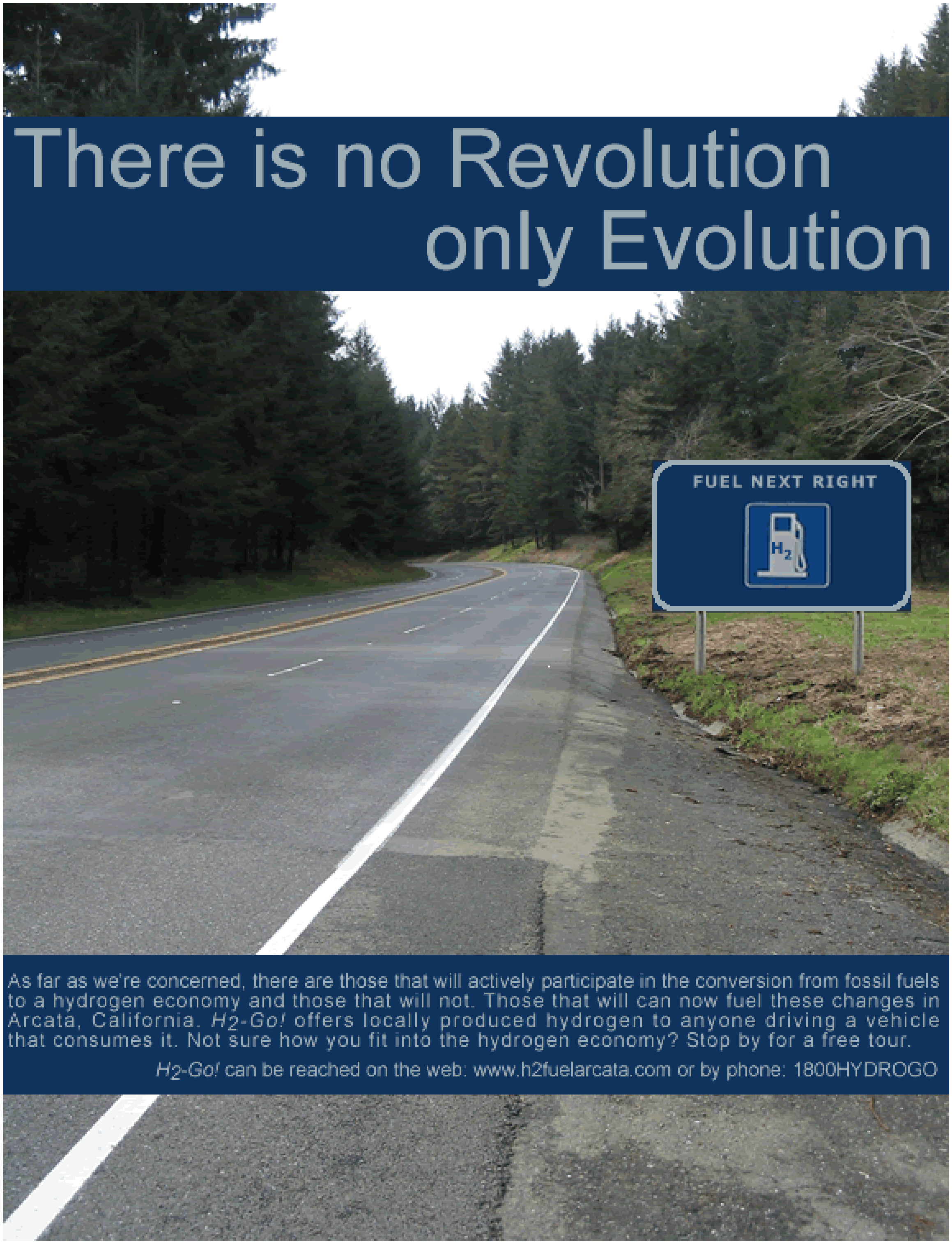
Energy in the form of hydrogen is considered an energy carrier, not an energy source. Hydrogen is an evolving technology in which all citizens must become active participants. The station will include a small formal public education facility to explain these ideas to the community. *H_2-Go!* will have tours every Friday and will feature displays that illuminate common myths about hydrogen and describe how hydrogen can be produced locally. The tours will detail the energy balances involved in hydrogen production and use with special emphasis on the need for energy conservation. Two-fold information pamphlets will be produced for distribution. RESU has offered to design the fliers and distribute them in the surrounding community.

5.2 Marketing and Advertisement

In order to actively promote the fueling station, an advertising campaign will be implemented to reach out to any and all potential customers. Cox Rasmussen & Co. Inc. has been hired to head the campaign. The platform is subtly aggressive, supporting the shift for a hydrogen economy with the pretense that "If you don't participate, you are going to be left behind".

Cox Rasmussen & Co. Inc. will provide an informational campaign targeting local media, including strategic billboard location, print, radio and television advertising. A detailed estimate is included in **Appendix H**.

One-Page Advertisement



As far as we're concerned, there are those that will actively participate in the conversion from fossil fuels to a hydrogen economy and those that will not. Those that will can now fuel these changes in Arcata, California. *H2-Go!* offers locally produced hydrogen to anyone driving a vehicle that consumes it. Not sure how you fit into the hydrogen economy? Stop by for a free tour.

H2-Go! can be reached on the web: www.h2fuelarcata.com or by phone: 1800HYDROGO

Figure 3- One-page advertisement for *H_2-Go!* fueling station (Pearlman, 2004).

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Appendix A

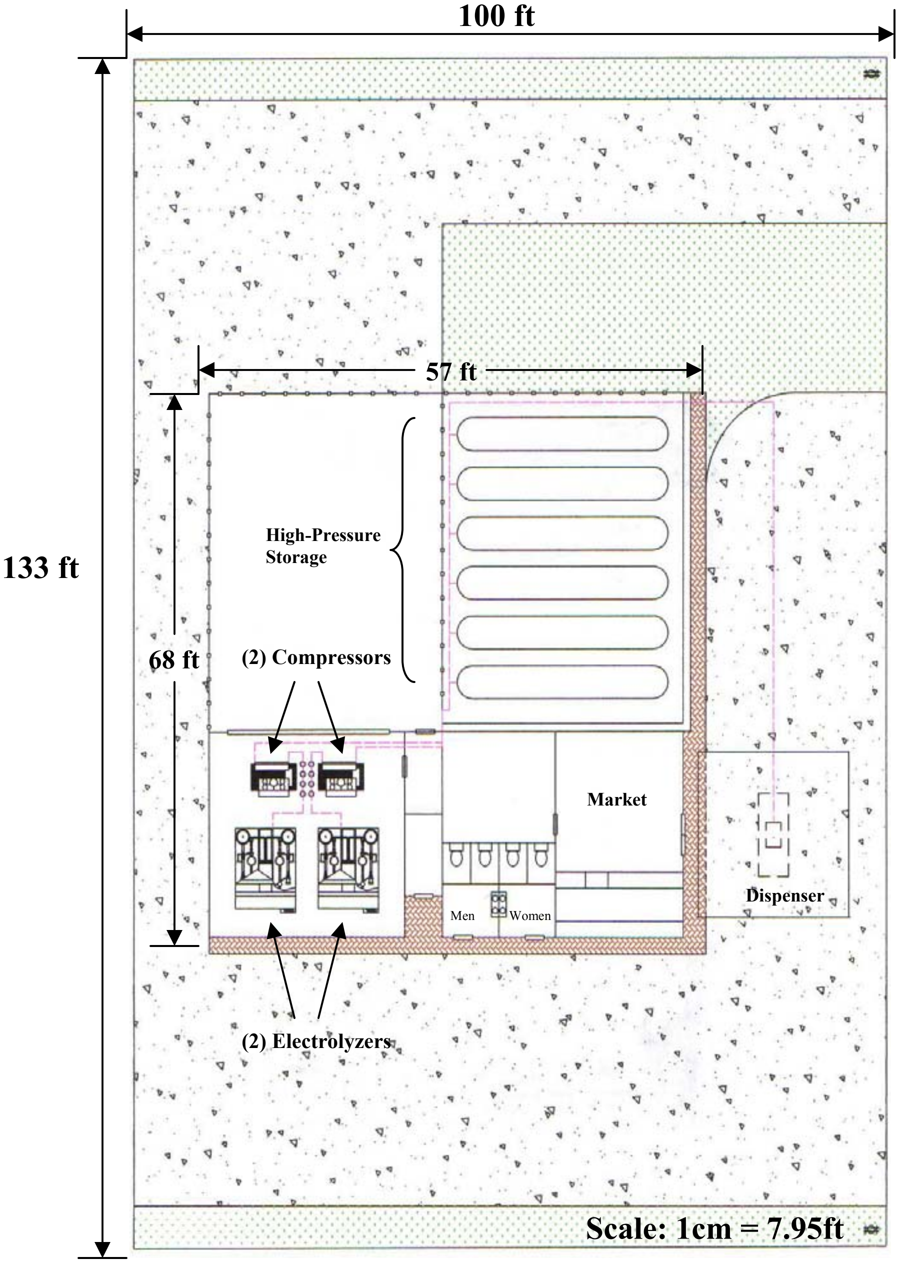

Figure 4- A plan-view schematic of the fueling station site (Adame, 2004).

Appendix B

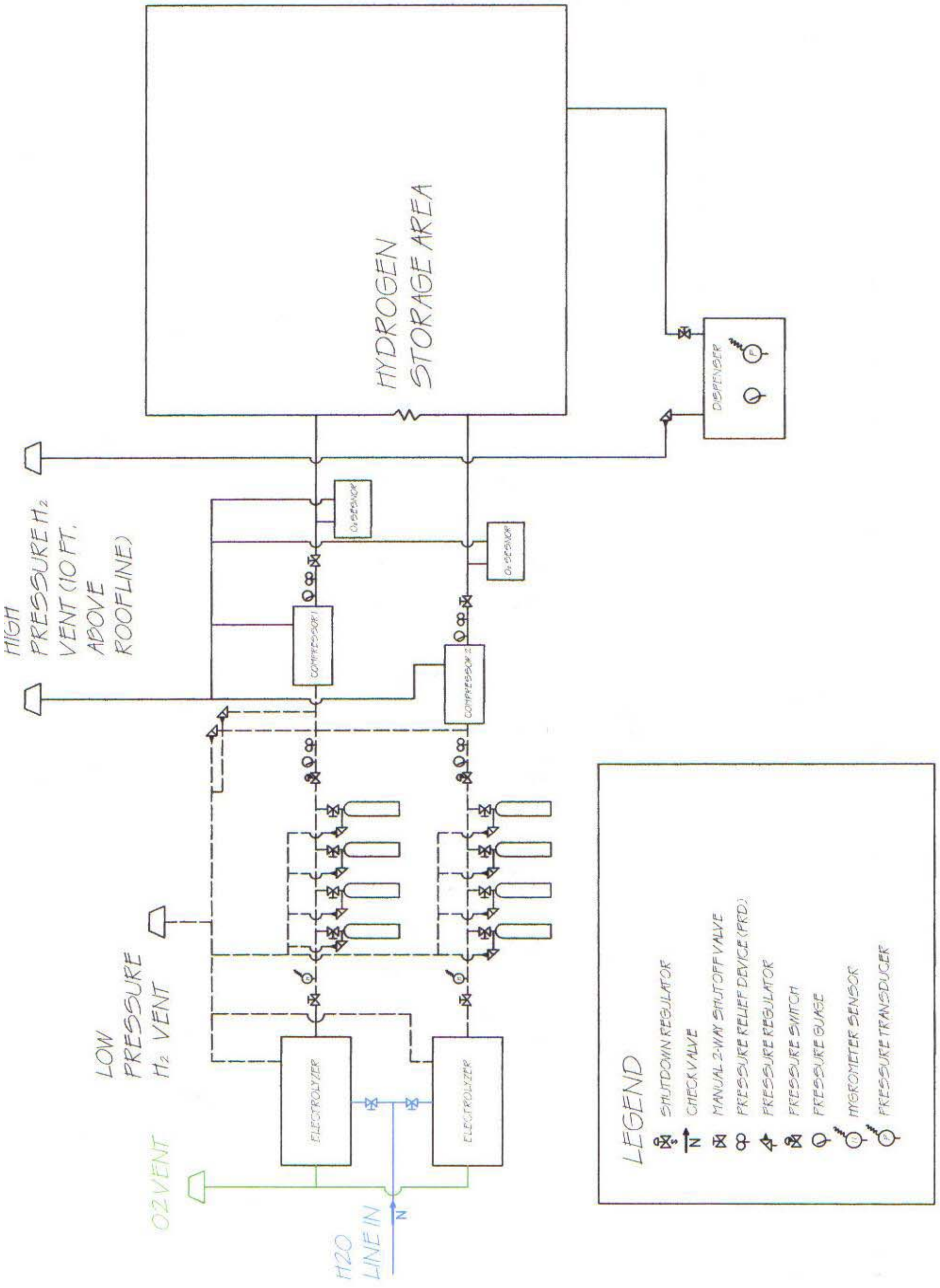

Figure 5- Flow chart schematic for the hydrogen plumbing system (Gopal et al., 2004).

Appendix C

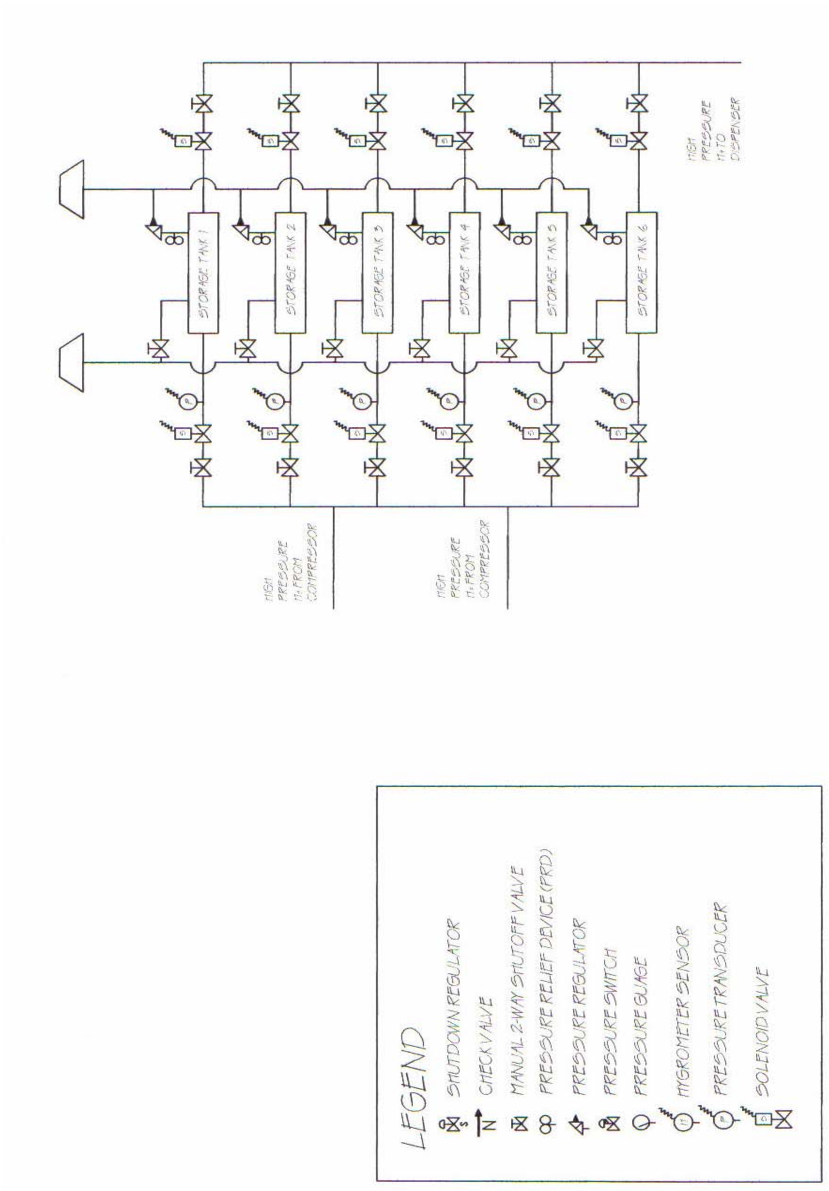

Figure 6- Flow chart schematic for the storage tank plumbing (Gopal et al., 2004).

Appendix D

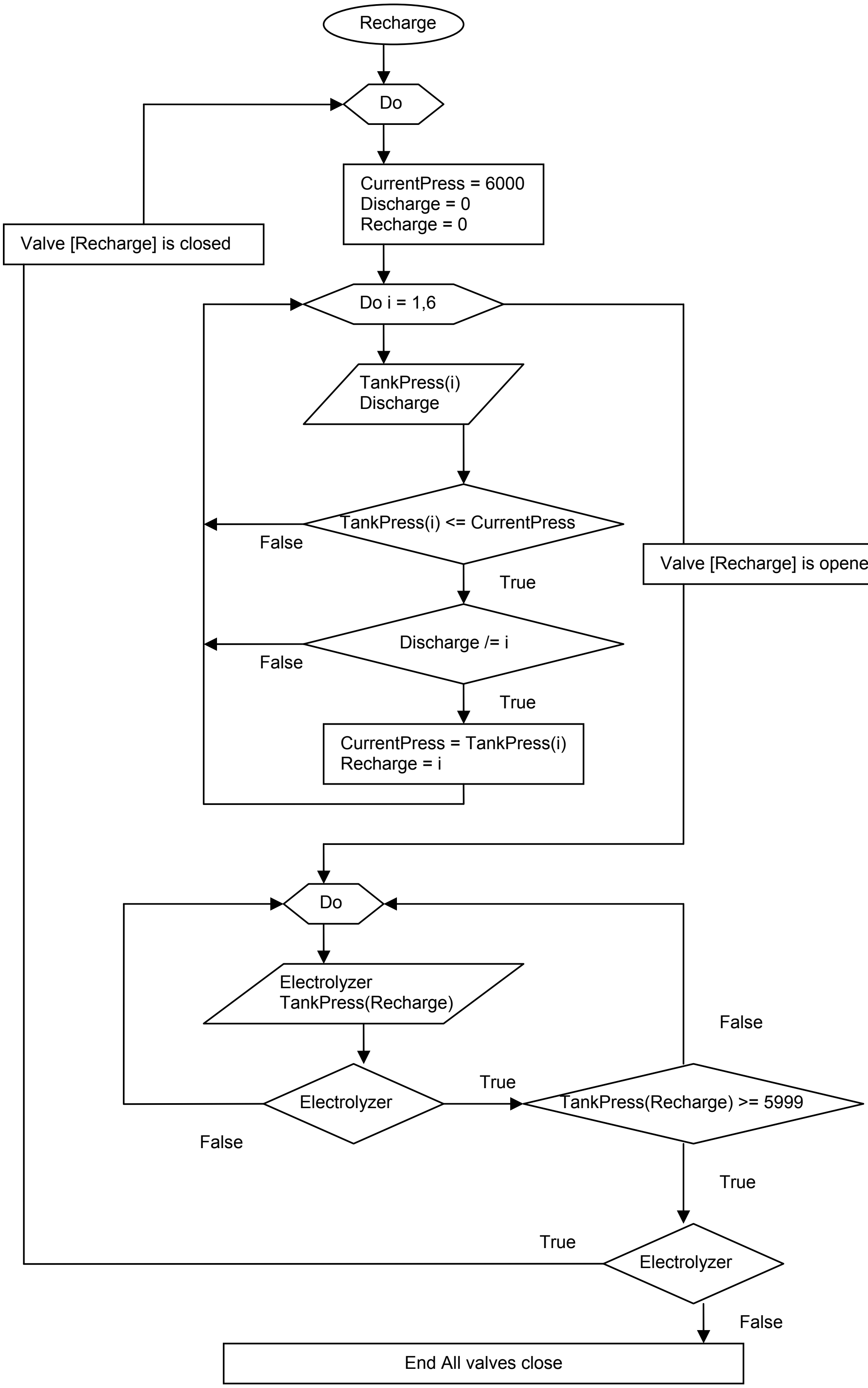

Figure 7- Logic flow chart for the recharging of the storage tanks (Williams, 2004).

Appendix E

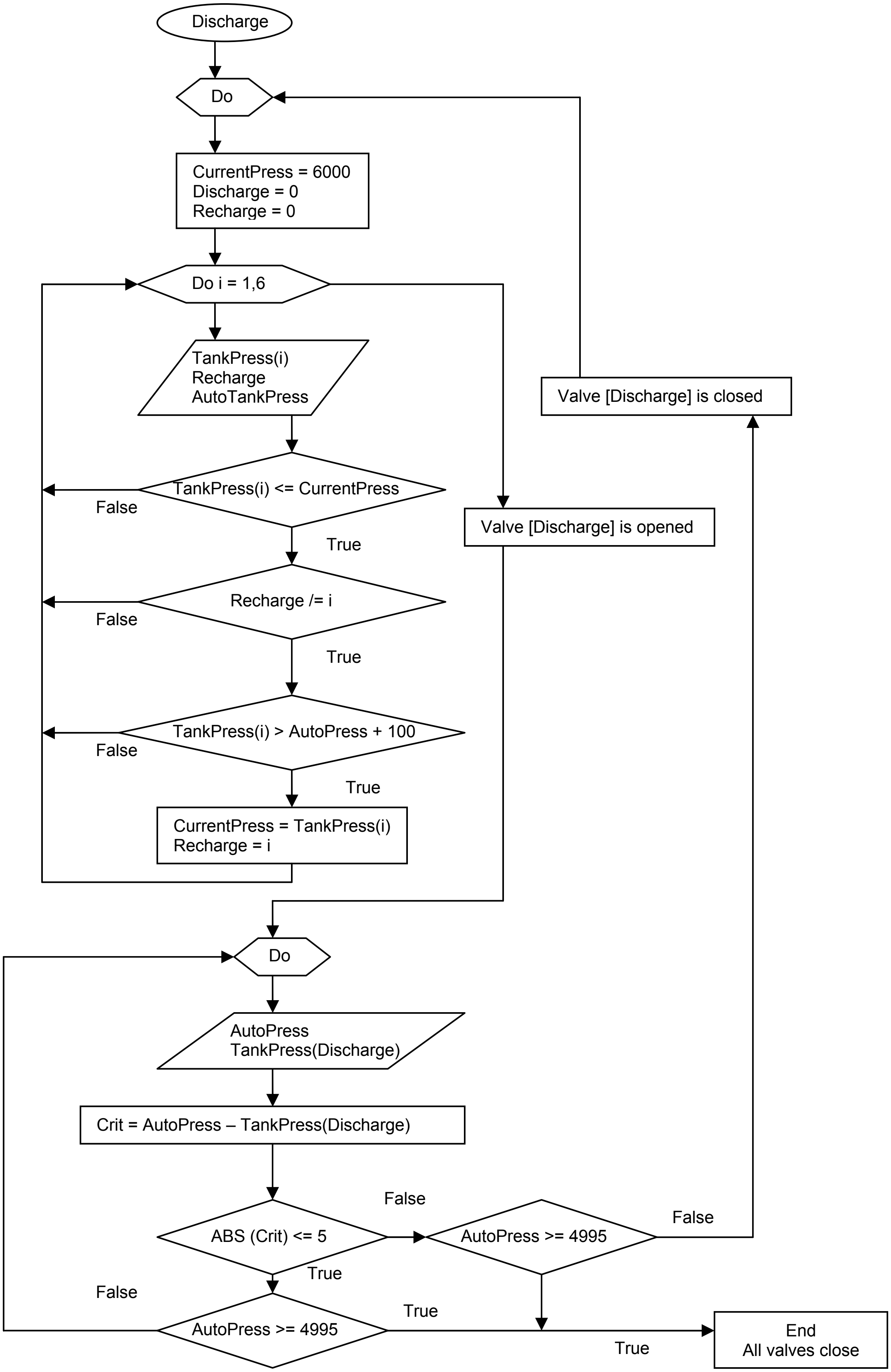

Figure 8- Logic flow chart for storage discharge algorithm (Williams, 2004).

Appendix F

Figure 9- Front right view of the fueling station. (Adame, 2004)

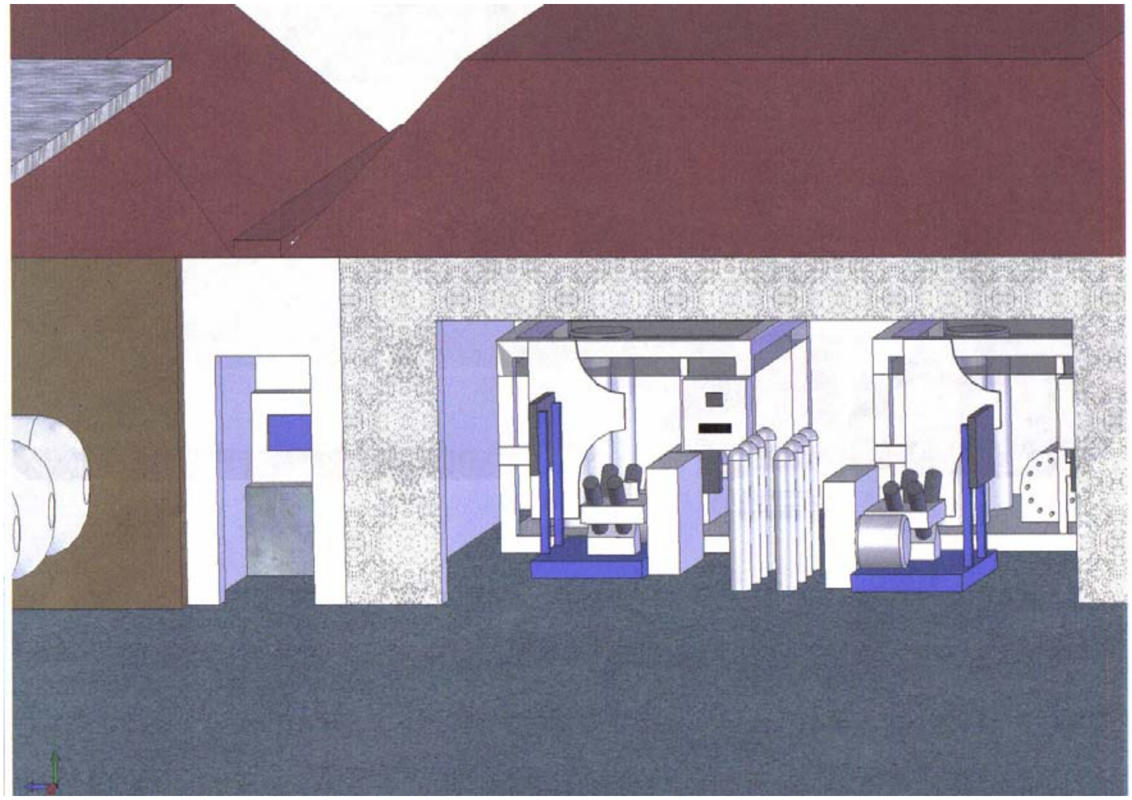

Figure 10- Rear view of fueling station with inside view of utility shed (Adame, 2004).

Appendix G

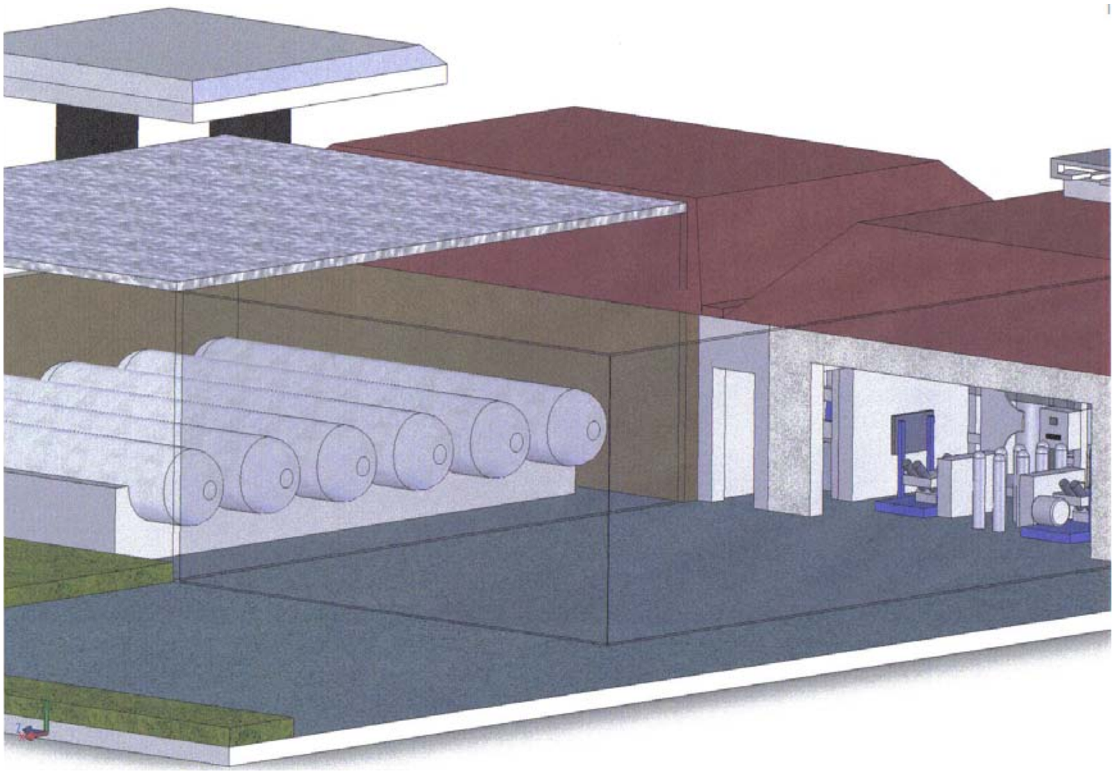

Figure 11- Rear right view of the fueling station (Adame, 2004).

Figure 12- Hydrogen Dispenser (Adame, 2004).

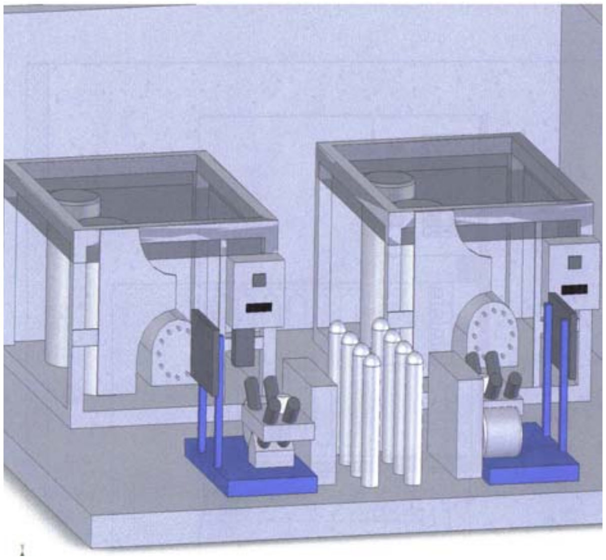

Figure 13- Electrolyzers, Compressors and Ballast Tanks (Adame, 2004).

Appendix H

Job Estimate

Description: Hydrogen Refueling Campaign

Date: 2/24/04
Client: HSU- Environmental Resources Engineering Department
Contact: Dave Carter
CRC Job Number: 00040205

The following estimate includes costs for developing an informational campaign to inform local residents of the benefits of hydrogen powered cars, as well as the possible construction of a hydrogen refueling station in our local area. The following pieces would be developed. This estimate does not include printing of billboard, additional posters, etc or media placement for newsprint, radio and television. Costs will be developed when further information and specifications are delivered from client. Client has stated that rough concept and design has been developed and will deliver such elements when needed.

Print Ads- Development of 2 unique black-and-white print ads for placement in various newsprint publications.

- Billable time includes concept development, design, copywriting, art direction, production, proofreading account service, and project management
- Estimate does not include photography or distribution of completed ads to media

Print Ad Estimate: $1,325.00 – $1,375.00

Radio Ads- Development of 2 unique, 60 second radio ads for placement on various local stations.

- Billable time includes copywriting, proofreading, account service, project management, recording, editing, and mixing
- Estimate does not include voice talent or distribution of completed ads to media

Radio Ad Estimate: $650.00 - $750.00

Television Ad- Development of one, 30 second radio ad for placement on various local stations.

- Billable time includes script writing, storyboarding, art direction, proofreading, video editing, audio editing, animation, account service, and project management, recording, editing, and mixing
- Estimate does not include voice talent or distribution of completed ads to media

Television Estimate: $1,550.00 - $1,600.00

Billboard- Development of a 12' x 24' billboard.

- Billable time includes design, art direction, production, proofreading account service, project management, and pre-press file preparation
- Estimate does not include printing

Billboard Estimate: $750.00 - $800.00

Total Estimate: $4,275.00 - $4,525.00
Deposit: $1,425.00*

*1/3 of low estimate is due at signing. Production work that exceeds deposit will be billed monthly as it is accrued, and will not exceed the high estimate.

Please sign and return to Cox Rasmussen & Co., Inc. so that we can proceed with your project. Thank You!

Authorized Signature
We've developed this estimate based on the number of revisions it typically takes to produce a finished campaign. This allows you to make the following changes:
2 revisions to copy prior to design
2 revisions to design
If you wish to make additional changes, they can be accommodated; however, a change order will be issued to cover the associated costs, which would be billed at an hourly rate.

This is an estimate, not a quote. The above estimate is for described work only and is valid for a period of 30 days from the date of the estimate. All printing estimates fall under guidelines established by the printing industry, which guarantee a total quantity of 10% over or under the quantity shown on the estimate. Dollar amounts charged will be adjusted to fit actual printed quantity. Does not include shipping charges or applicable sales tax. Client's signature authorizes Cox Rasmussen and Company to bill the client for the charges associated with producing the above stated product/s. Client will not be charged in excess of the high estimate unless a change order has been issued and authorized.

2830 F Street, Eureka, CA 95501 (707) 445-3101 Fax: (707) 445-255 email: sequoya@coxrasmussen.com

Appendix I

Table 17- Comparison of Selected World Gas Prices (USDOE, 2004).

Two month average $/gallon from 1/5/04 - 2/23/04	
Belgium	$4.65
France	$4.77
Germany	$5.10
Italy	$5.03
Netherlands	$5.66
UK	$5.29
Average	$5.08
US average over same period	$1.80
% Difference between U.S. and average	64.59%

http://www.eia.doe.gov/emeu/international/gas1.html

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Appendix J

Table 18:Sample PG&E E-19 rate calculation worksheet

Fairhaven - Summer				**Fairhaven - Winter**				**Summer Data:**	
	Rate	Amnt			Rate	Amnt		Demand	509.184089
								On Peak	509
Demand Charges				Demand Charges				Part Peak	509
On Peak	3.59	1,827.97						Max Dem	509
Part Peak	0.80	407.35		Part Peak	0.8	450.40			
Max Demand	2.55	1,298.42		Max Demand	2.55	1,435.65		Energy	
								On Peak	63,917
PG&E Charges				Energy Charges				Part Peak	77,141
On Peak	0.042570	2,720.95						Off Peak	214,938
Part Peak	0.041980	3,238.40		Part Peak	0.04233	5,971.01		Total	355,996
Off Peak	0.041910	9,008.05		Off Peak	0.04193	9,012.35			
								Winter Data:	
Fairhaven Charges	0.06784	24,150.80			0.06784	24,150.80		Demand	506.319219
								Part Peak	563
D.A. from PG&E tool		$6,082.89				$4,196.67		Max Dem	563
Total Bill		**39,118.20**		**Total Bill**		**39,134.16**			
Total Bill w/D.A		30,233.69				28,347.48		Energy	
annual electricity cost		**$469,514.15**		$351,487.02				Part Peak	141,059
average monthly electricity cost		$39,126.18		**Billing Days**	30.3			Off Peak	214,938
average daily electricity cost		$1,304.21		Weekend days per month	8.65714286			Total	355,996
average hourly electricity cost		$54.34		Weekdays per month	21.6428571				
average electric rate ($/kw-hr)		$0.11		Eltrlzr hrs	21.26				
								kW	kWh
mini mart elec	$/month	kw	kwh		H2 compressor			10	238
summer	1750	20.05408874	1.167		Electrolyzer peak demand			470.4	
winter	1500	17.18921892	1		Misc equip power (kW)			5	119
estimated rate($/kW	0.12				Electrolyzer energy consumption				11195.52
hrs/month	727.2				IAQ compressor (kW)			3.73	88.774
					totals			489.13	11641.294

Table 19: Station specifications

	Existing Specifications for Hydrogen Fueling Station Design										
H2 density at NTP			0.084	kg/m3							
H2 density at STP			0.09	kg/m3	=	0.002549	kg/ft3				
Gallon of Gasoline Equivalent (GGE) Calculations											
HHV	1 gal of gas		=	1	kg H2	=	392.3	scf	=	11.9	Nm3
LHV	1 gal of gas		=	1.1	kg H2	=	431.6	scf	=	13.1	Nm3
Station Requirements:			50	(veh./day)		**Hydrogen Energy Content**					
			3	(kgH$_2$/veh.)		HHV	142	kJ/g			
		=	150	(kgH$_2$/day)		LHV	120	kJ/g			
		=	1785.7	(Nm^{3}H$_2$/day)							
		=	150	(GGE HHV/day)		**Gasoline Energy Content**					
						HHV	143175	kJ/gal			
		Peak:	20	(kgH$_2$/hr)		LHV	125000	kJ/gal			
		=	238.1	(Nm^{3}H$_2$/hr)							
					Max operation hours per day including maintenance as per TBE						23.8
Other Specifications and Assumptions:					Max H2 production per operating day as per max operating hours						1999.2
					Max kg H2 per day						167.9328
	Total Station Footprint:		14,440	(ft^2)	Max cars per day						55.9776
	H$_2$ Delivery Pressure:		5000	(psig)							
	H$_2$ Vehicle MPG:		60	(miles/kgH$_2$)		Electrolyzer capacity (Nm^3/hr)			84		
	Standard Veh. MPG:		27.5	(MPG)		Total hours of operation/day			0.00		
	Compressor Costs:		40	($/day)		10 year cost (capital + electricity)			$879,984		
						Daily production constraint (Nm^3)			0.00		

Table 20:Sample PG&E Direct Access rate calculation result

SUMMARY OF CHARGES				
		Bundled	**Non-Continuous DA**	**Continuous DA**
Transmission		$1,036.99	$1,036.99	$1,036.99
Distribution		$1,899.83	$1,899.83	$1,899.83
Public Purpose Programs		$1,207.77	$1,207.77	$1,207.77
Nuclear Decommissioning		$116.27	$116.27	$116.27
Bundled DWR Bond		$1,665.37	n/a	n/a
Generation		$33,206.16	n/a	n/a
DA DWR Bond		n/a	$1,665.37	n/a
DA DWR Power		n/a	$8,461.88	n/a
Franchise Fee Surcharge		n/a	$157.57	$157.57
Total Charge		$39,132.39	$14,545.68	$4,418.43