

THE COOPER UNION FOR THE ADVANCEMENT OF SCIENCE AND ART
ALBERT NERKEN SCHOOL OF ENGINEERING

Redesign of the StarFuel System's Hydrogen Utilization Module
to Include Three Ten-Watt BCS Technology Proton Exchange
Membrane Hydrogen-Air Fuel Cells

by

Griffin Travers Reilly

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Engineering

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This thesis was prepared under the direction of Dr. Joel W. Hollenberg, Professor of Mechanical Engineering, and has received approval. It was submitted to the Dean of the School of Engineering and the full Faculty, and was approved as partial fulfillment of the requirements for the degree of Master of Engineering.

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Dr. Joel W. Hollenberg

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This project would never have been without the vision of a reliable pollution free source of energy by my advisor, Dr. Joel W. Hollenberg, P.E. Ph.D., and I thank him for allowing and helping me include this small addition to such a *grand goal*.

I would also like to thank Dr. Hollenberg's previous graduate and senior mechanical engineering students who constructed the system for their concerted effort in documenting their work with such clarity. Their efforts for "some future student" was gratefully received.

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Finally I would like to thank my loving parents, who have been an unwavering source of support. They can never know how much they have given me.

Abstract

The *StarFuel System* is both an integrated solar-hydrogen energy conversion pilot power plant, and a test station for the acquisition of characteristic data from its state of the art components and their interactions. The Hydrogen Utilization Module was built in 1995 around a 130 Watt Proton Exchange Membrane (PEM) fuel cell from *A.F. Sammer*, and in 2000 supplied a 30 Watt PEM fuel cell from *H Power*, both of which have been returned to their manufacturers. This work is focused around the redesign of the Hydrogen Utilization Module to include three *BCS Technology* 10 Watt hydrogen-air PEM fuel cells, enhancing its role as a fuel cell test stand as well as replacing a key component needed for the realization of the system's original concept.

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Chapter 1: Introduction

1.1 General Overview of the StarFuel System

Formerly named the Photovoltaic Energy Conversion System (or PECS), the *StarFuel System* is an operational pilot power plant located in Room 6E of the Albert Nerken School of Engineering at The Cooper Union for the Advancement of Science and Art. This patented system uses the unsteady power from a solar array to produce hydrogen, which is then stored and later used as the reactant in fuel cells to supply constant output to an electrical load [1]. The original concept for the system was conceived by Dr. Joel W. Hollenberg, P.E., Ph.D. in 1974. The purpose of such a system is to harness the emerging hydrogen technology, from fuel cells to production and storage units, in the most environmentally friendly manner. The only byproducts of the system are heat, which is dispersed through natural convection, water, which is piped to the New York City sewage system, and oxygen gas, which aerates the effluent [4]. Within nearly thirty years of research and development by Dr. Hollenberg and Cooper Union students, the system has taken form within five modules:

1. The Photovoltaic Module (PVM) is the energy input of the system, comprising mainly of the solar array on the roof of the Albert Nerken School of Engineering, and the passive load matching device used in the unsteady feed of the electrolyzers.
2. The Hydrogen Generation Module (HGM) consists of the three water electrolyzers and the purification system to output hydrogen gas at 99.9999% purity.

3. The Hydrogen Storage Module (HSM) uses a metal hydride to store the produced hydrogen gas as a stable solid.
4. The Hydrogen Utilization Module (HUM) consists primarily of a fuel cell stack used to produce the end product, steady electricity.
5. The Master Control and Data Acquisition System Module (MCDASM) regulates and safely operates all parts of the StarFuel System via computer and control panel interfaces [2].

Figure 1.1 shows a schematic diagram of the system, broken down into its constituent parts. All five modules were successfully run as a completely integrated system for the first time on April 10, 1997 by graduate student, Mr. Lomma [5].

1.2 Statement of Problem

The hydrogen-oxygen proton exchange membrane (PEM) fuel cell, model AFS 125-4, that Mr. Lomma used to complete the StarFuel System was on loan from *A.F. Sammer*, and was returned during the summer of 1997, leaving the Hydrogen Utilization Module incomplete. Ms. Doris Chin returned the system to completion in her thesis work with the retrofitting of the HUM to accept a 30 Watt hydrogen-air PEM fuel cell that was a development model on loan from *H Power*. This new stack did not require the research oxygen needed by the first, as it pulled the necessary oxygen from the air, through forced convection. Chin successfully ran the integrated system with the new fuel cell on April 3, 2000 [3]. However, shortly after the completion of her work the fuel cell was returned to *H Power*, once again leaving the HUM, and the StarFuel System, incomplete. [2]

In work towards the completion of their Senior Project, Hobden *et al.* compiled a database on fuel cell manufactures in an attempt to find a suitable replacement to the unit

lost the previous year. The added safety and convenience of an air-breathing stack was still desirable, however the unit had to adhere to a design of no moving parts (consistent throughout the StarFuel System.) These combined requirements ruled out units with compressors on the air intake or fans producing forced convection, which put a considerable limitation on suitable manufactures. At the time, the industry was leading towards air-breathing stacks with both compressors and fans because of the increase in stack efficiency. Only one manufacture was found that produced the desired unit, *BCS Technology*. They produce only one unit that meets the desired specifications, with a power output of 10 Watts. Towards the end of their work, Hobden *et al.* purchased one 10 Watt hydrogen-ambient air breathing PEM fuel cell stack from *BCS Technology*. The unit was attached to the StarFuel System temporarily to ensure it was functioning, and then returned to storage. [2]

This work is focused on the design needed to complete the StarFuel System's Hydrogen Utilization Module once again with the installation of this 10 Watt stack. Additionally, in the interest of furthering the system's role as a fuel cell test station, two identical units are added in the design, allowing for tests of multiple fuel cell stacks in an integrated system supplying a variable load up to 30 Watts.

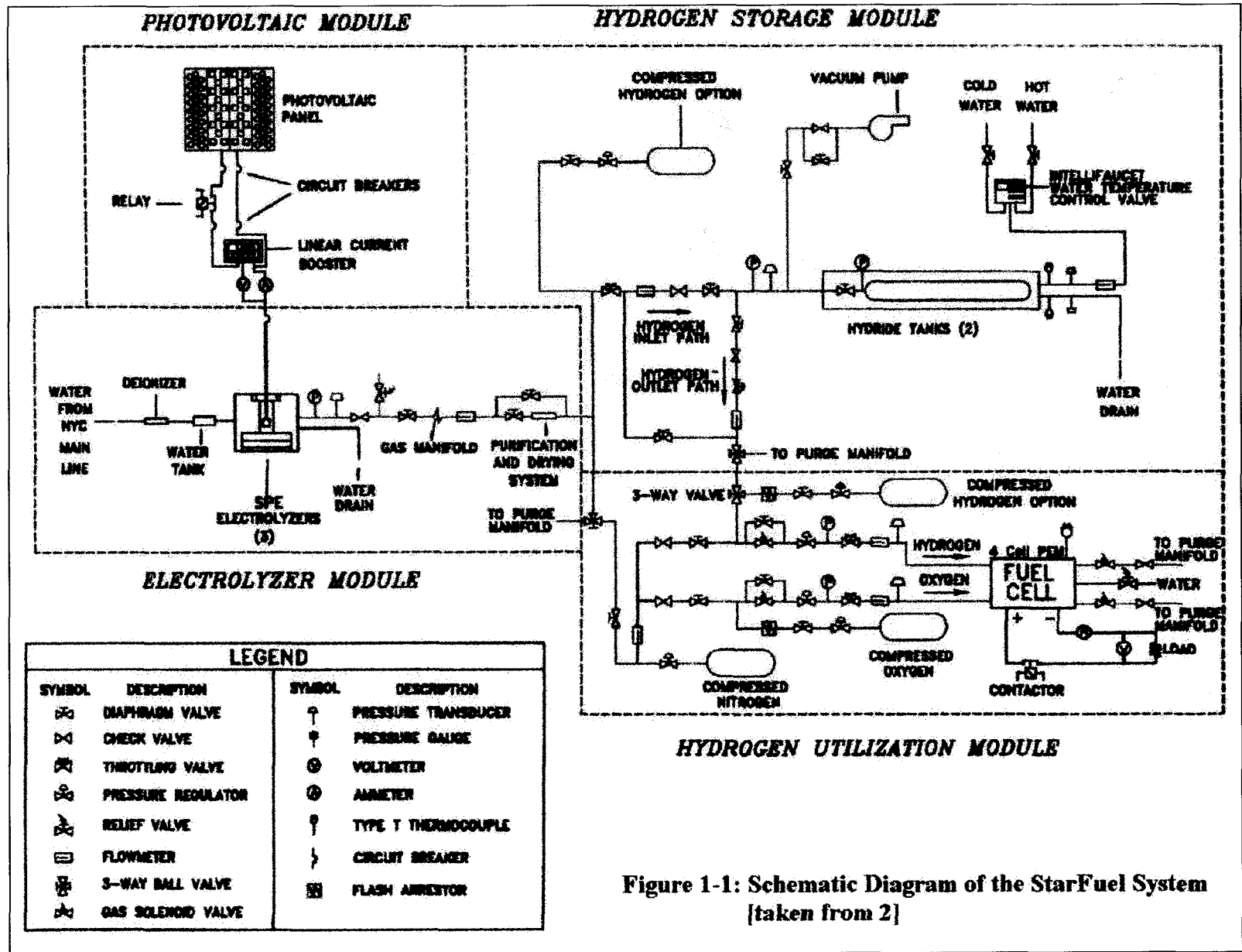


Figure 1-1: Schematic Diagram of the StarFuel System [taken from 2]

1.3 Current Status of the Photovoltaic Module (PVM)

The photovoltaic array on the roof of the Albert Nerken School of Engineering is the heart of the PVM, and the source of power for the StarFuel System. The array consists of two *Arco* M-73 panels rated at 40W each, two *SolarWest Electric* ASI-16-2000 panels rated at 35W each, and two *AstroPower* AP-30 panels rated at 30W, for a total maximum power output of the PVM of 210W [2]. This power is transmitted to the basement of the building to Room 6E, where the remainder of the StarFuel System is housed, via a No. 6 gauge electrical wire. In route, a *Bobier Electronics* LCB-20 linear current booster is used as a load-matching device for the power between the PVM and the HGM. It converts excess voltage from the array into current passively, that is without an additional source of energy and thus no parasitic losses occur. The module is installed in accordance with all New York City electrical safety codes, including circuit breakers and other safety equipment [4].

In addition to the power line, an additional line wires the temperature and insolation for data acquisition. The insolation that the array is subjected to is measured by a *Weathertronics* 3120 pyranometer located above the array. This unit has sustained some damage, and the protective Pyrex dome is cracked, along with the silicon cell. Hobden *et al.* purchased a replacement: a *Kipp & Zonen* CM3 Pyranometer. This unit has not been installed as of date [1]. Figure 1.2 is a photograph of the photovoltaic array with the *Weathertronics* pyranometer.

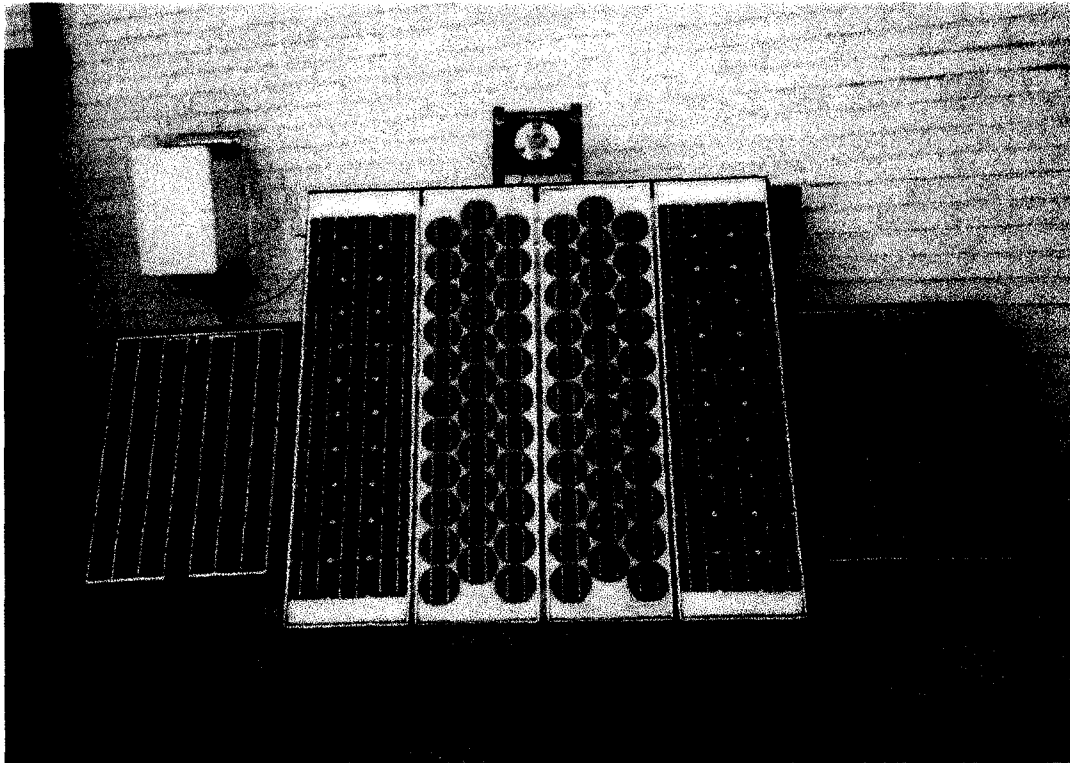


Figure 1.2: The Photovoltaic Array located on the Roof of the Engineering Building [taken from 2]

1.3 Current Status of the Hydrogen Generation Module (HGM)

The unsteady power from the PVM is sent directly to three *Aadco* 3-cell solid polymer electrolyte (SPE) electrolyzers, each with a maximum rated output of 0.225 standard liters per minute (slpm) of hydrogen gas at up to 100 psig. Each unit operates at a maximum current of 12 Amps within a voltage range of 4.5 to 6.8 volts, direct current. They are rated to produce 22.5 cubic centimeters per minute (ccm) of hydrogen for every ampere of inputted current, not to exceed 14A. The rated voltage at the optimal amperage of 10A is 6.8V, which produces 225 ccm of hydrogen, and the minimum operating voltage is 4.5V [2]. Figure 1.3 is a schematic of one *Aadco* unit.

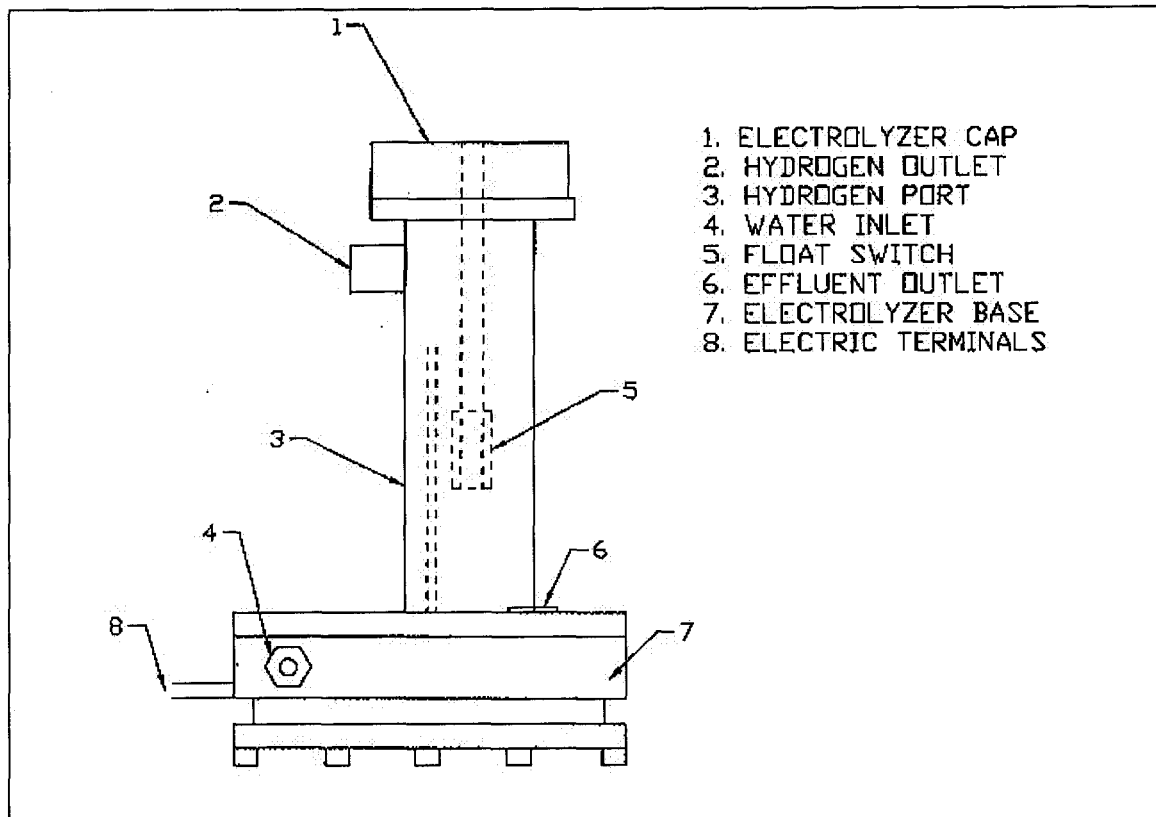


Figure 1.3: Schematic of an Aadco Electrolyser [6]

The three cells are located at the base of the unit. The water inlet requires deionized water with a resistance of at least 30kΩ, which is supplied by a *Barnstead Bantam Model 09-033-10* water deionizer fed from the New York City water supply. As the water builds in the unit, the regulation of flow into each unit becomes necessary to prevent overflow, which is the cause for the float switch. When the reservoir is filled, the float switch triggers a *Cole-Parmer Model L-06469-98* solenoid that cuts the water feed until the unit requires additional input [5]. After decomposition of the water into its constituent parts, the oxygen and effluent are vented through the relief valve to the New York City sewage system, and the hydrogen bubbles through the hydrogen port and out the hydrogen outlet [2].

The output lines leaving the electrolyzers are each fitted with a *STRA-VAL* pressure relief valve rated at 100 psia (preventing damage to the electrolyzer unit), and then a *Matheson* Model 401V check valve (preventing the H₂ from back-flowing into the unit.) Next, a *Setra* Model 280 E pressure transducer, along with a parallel *Ashcroft* Type 1082 pressure gauge, measures the pressure of the outputted hydrogen. Next the products of all three electrolyzers are joined in a gas manifold. On its way to the purification system, the hydrogen's mass flow rate is measured by a *Omega* Model FMA-217, 0 to 2 slpm mass flowmeter.

The excess water vapor is then removed using two *Supelco* Molecular Sleeve Desiccant Tubes, leaving the last task of oxygen removal. This is accomplished by a *Mathson* Semi-Gas Systems Nanochem Hydrogen Purifier, and a *Resource System Inc.* Catalytic Purifier. The result is an output of hydrogen gas with an acceptable purity level of one part-per-billion oxygen and water vapor [5].

1.5 Current Status of the Hydrogen Storage Module (HSM)

The units used for the storage of the hydrogen produced from the HGM are two *Ergenics* ST-45 hydride storage tanks rated to hold 45 standard liters of hydrogen each. They contain a mischmetal-nickel-aluminum (Mm_{0.97}Ni_{4.5}Al_{0.5}) hydrating alloy, commercially known as HYSTOR-208 [6]. The alloy is held in seven individual stainless steel tubes surrounded by a water jacket that provides the heat exchange into and out of the alloy needed for the discharging and charging of the tanks, respectively. The temperature of the water entering the water jackets is controlled with an *Intellifaucet* automatic water mixing valve that controls the ratio of cold New York City tap water, and water heated through a *Wattrimmer* Model 3E530J 119-gallon water heater. The

pressure and mass flow rate into and from each tank is measured by *Setra*-204 pressure transducers for the digital, and *Omega* PGT-45-30v/200 type T pressure gauges for analog readings, and two digital flow meters: a FMA-217 and FMA-219 [5].

Figure 1.4 shows a schematic of the HSM, and it is important to note that this layout allows for the simultaneous charging of either tank, while the other is discharging. Additionally, the system can transfer from discharge of one tank to the other with no fluctuation in mass flowrate to the HUM [6].

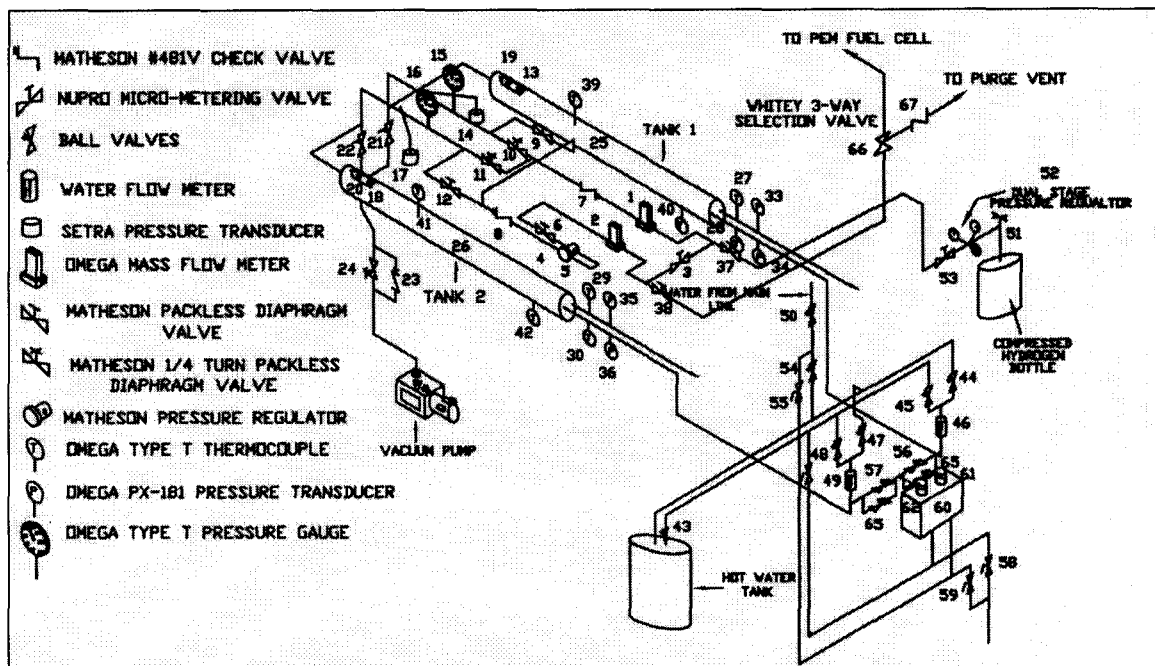


Figure 1.4: Schematic Diagram of the Hydrogen Storage Module [4]

1.6 The Hydrogen Utilization Module (HUM)

1.6.1 Background

The fuel cell that is used with the StarFuel System comprises the Hydrogen Utilization Module's core, and the remainder of the module is a test stand built around the stack to supply, monitor, and control. As such, it has been the requirements of past

stacks that have shaped the overall design and functionality of what remains today as the HUM. In November 1993, Mr. Dean Modroukas leased a four-cell hydrogen-oxygen PEM fuel cell stack from *A.F. Sammer Corporation*, model AFS 125-4, as part of his thesis work; the birth of the Hydrogen Utilization Module. This stack required both high purity hydrogen and high purity oxygen for operation, thus requiring the controlled delivery of both the fuel and oxidant. A *Matheson* compressed research oxygen tank supplied the oxygen at a purity of 99.9998%. The test stand was designed somewhat symmetrically, with the control and monitoring equipment for the research oxygen on the left, and for the hydrogen on the right. Additionally, a tank of compressed research hydrogen (99.9999% purity) was installed as an option to test the HUM independently from the other modules.

The fuel cell had a maximum power output of 135 Watts at 50 Amps and stack voltages of 2.65 VDC [7]. Thus the monitoring equipment, including voltage regulators, pressure gauges and transducers, and mass flow meters, as well as the control equipment, including the valves and solenoids, were all designed for a higher power, pressure, and flow, sacrificing some sensitivity.

During the first test run on March 25, 1995, the stack had an internal fire after only a few minutes of connection. When the repaired stack returned from the manufacture, Mr. Timothy Lomma had taken over Modroukas' work. Lomma found that a possible cause of the fire could have been in the improper purging of the fuel cell, prior to the initial test. He added to the stand a tank of ultra-high-purity (UHP) nitrogen and piping necessary to purge the module (including the fuel cell) with it, thus flushing any reactants from the system. He also changed the piping layout of the module to ensure that

the dangerous mixture of oxygen and hydrogen could never form within the stand itself, with added precaution [5]. Figure 1.5 shows the Hydrogen Utilization Module as it existed after Lomma's work, taken directly from his thesis.

In the summer of 1997 the *AF Sammer* stack was returned to the manufacturer. Ms. Doris Chin replaced it with another unit during her thesis work in 2000, a 30 Watt PEM hydrogen-air 30-cell stack loaned from *H Power* without cost. This fuel cell came with its own 12 volt DC powered fan which served primarily to circulate the ambient air through the stack, where it pulled the needed oxygen gas from. The immediate result was the removal of the *A.F. Sammer's* cooling fan, as well as the *Matheson* compressed oxygen tank, leaving half of the original stand with no further purpose [4]. This was a major note of Chin's work, the successful demonstration of an ambient-air breathing fuel cell stack from the produced hydrogen of the StarFuel System. The new fuel cell simplified the HUM's working components greatly, but the physical stand still has the remains of its past. The *H Power* stack was returned at the conclusion of Chin's work in the summer of 2000, along with its components, leaving the HUM physically unchanged (excluding the removal of the oxygen gas tank) from the completion of Lomma's work, and again without its vital component.

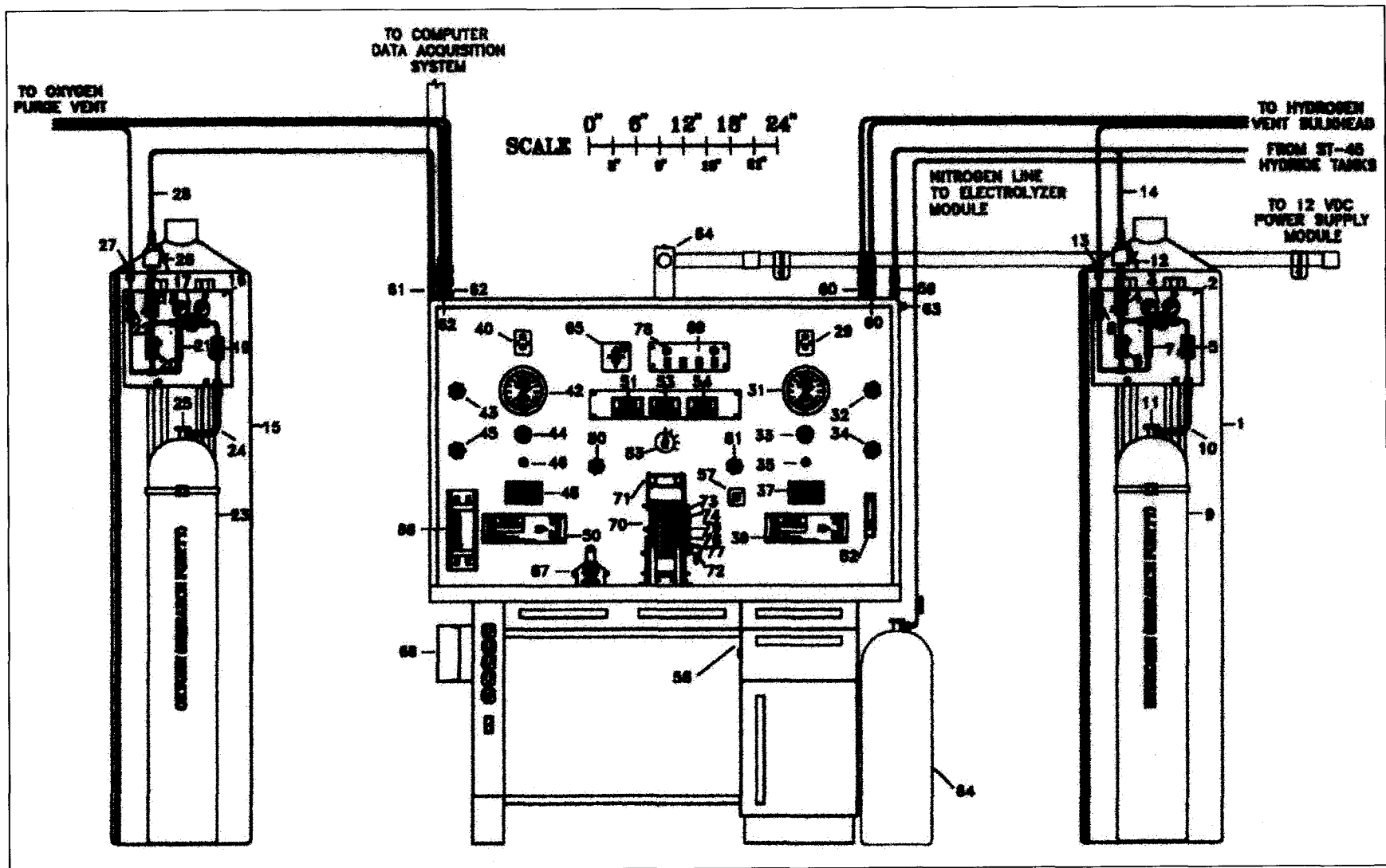


Figure 1.5: Hydrogen Utilization Module as of 1997 [taken from 5]

1.6.2 Current Status

Hobden et al. tested the *BCS Technology* fuel cell stack in December 2001 through the Utilization Module that exists today. At the time, the system had not been altered to accurately work within the pressure range of the new stack (0-2 psig) but the purpose of the test was simply to verify that the fuel cell was functioning. Hence they tried to simply get the HUM to function at its lowest possible hydrogen output [2]. The hydrogen entered the module through the test stand's inlet *Swagelok* bulkhead/check valve assembly (item 59 in Figure 1.5) and past the hydrogen process solenoid valve (30). The *Matheson* High Purity Panel Mount Regulator (33) is only rated for use between 4 and 100 psig, with very little sensitivity, however it was possible to use this equipment to achieve a pressure less than 2 psig. The *Omega Engineering* Analog Pressure Gauge (31) (rated between 0-150 psig) and the *Matheson* Pressure Transducer (36) (rated between 0-115 psia) measured the pressure downstream of the regulator to be within acceptable limits. Next, the mass flow was lowered to be less than 350 milliliter per minute with the *Matheson* High Accuracy Hydrogen Gas Needle Valve (35) which has a range of 0 to 2.8 standard liters per minute. The flow was measured downstream of the needle valve with the *Matheson* Flow Meter (38), and read by the *Matheson* Mass Flow Display Box (39). Finally, the hydrogen reached the fuel cell and the voltage was measured using an independent voltmeter [2].

These components are the only parts that are still necessary for the supplying the fuel cell stacks, however as is clearly seen they lack the sensitivity for the application. All the components, including those not mentioned here, are named in Table C.1. The *BCS Technology* stack was returned to storage, and the HUM is currently without a fuel cell

and thus in disuse. The additional two stacks were purchased over the summer of 2002, and were tested for operational status in the same manner as the first. They await permanent installation in storage as well.

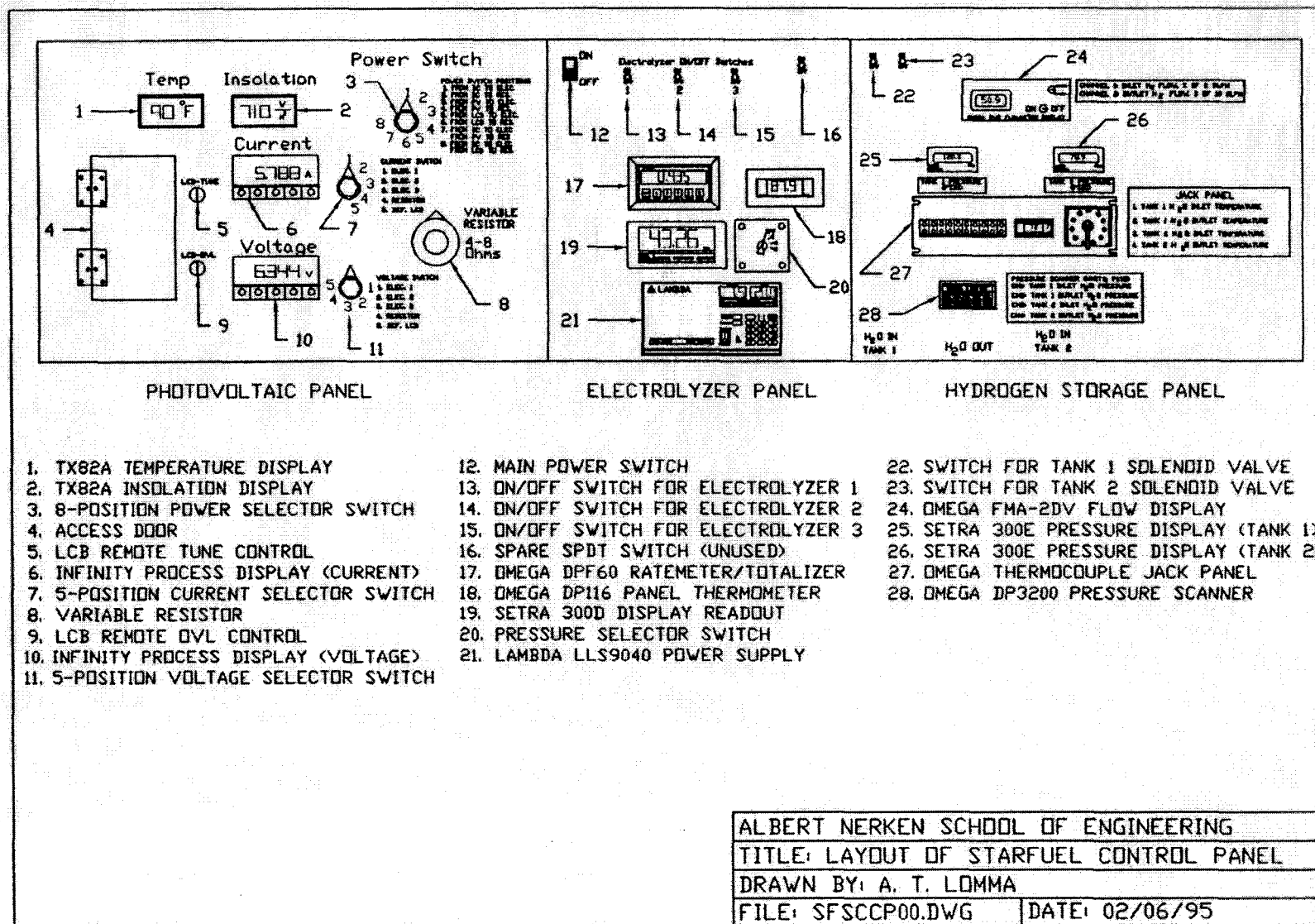
1.7 The Master Control and Data Acquisition Module (MCDASM)

The StarFuel System is a pilot plant, the first of its kind, and as such is a tool for research on the integration of the previous four modules; therefore it is necessary to record continuous data from the system for study. Additionally, it is required that the modules are controllable for integrated system runs. The Master Control and Data Acquisition Module, as its name suggests, does just this. Built into the design of every module, as stated above, are analog and digital data collecting devices such as pressure gauges and transducers. These devices coincided with the two interfaces for the user, an analog and a digital. The analog interface for the first three modules discussed is housed in a control panel located adjacent to the HGM and HSM units. Figure 1.6 shows the layout of this panel [6]. The digital signals are wired to three *Strawberry Tree* data acquisition boards, two ACPC-16-16 and one ACPC-16-16-C, which provide access to analog or digital signals for the computer. Each card has 16 differential analog inputs and 16 digital I/O lines. A maximum of fifteen cards can be operated together for a total of 240 digital I/O's and 240 analog inputs.

The computer is an *Advanced Logic Research* (ALR) Pentium-60 MHz computer with 16 MB of RAM, a *Colorado* 250 MB tape backup system, a 1 GB SCSI-2 hard drive, a 1.2 MB 5¼" floppy disk drive, a 1.44 MB 3½" floppy disk drive, and a 14" SVGA non-interlaced monitor. This computer is connected to an *Industrial Source* 486-33 MHz computer, with 8 MB of RAM and a 200 MB hard drive, via a peer-to-peer

Windows for Workgroups network with *Intel* EtherExpress Flash cards. Together, these computers serve as the data acquisition and control mechanism for the entire StarFuel System. For details on the wiring of the MCDASM, consult Mr. Krishendat Lakeram's Thesis, reference 6.

Figure 1.6: Layout of the MCDASM Control Panel [taken from 6]



Chapter 2: A Discussion of Fuel Cells

Fuel cells are by no means a new technology, but they are an emerging one. Their origin dates back to mid-1800 while the debate of which type of fuel would best supply the energy needs of the newly industrialized populace begun. As the internal combustion engine and cheap fossil fuels gained popularity, interest in fuel cell technology took a back seat. After World War II it spurred again, and a great deal of improvements were made by the National Aeronautics and Space Administration (NASA) as they sought an alternative to heavy, caustic batteries [8]. Today fuel cells promise a cleaner, more efficient, and ultimately cheaper future alternative to fossil fuel's current domination over our energy needs. This chapter is to help the reader understand how, as well as give the background for the work done at The Cooper Union within this field.

First the basics behind fuel cell technology is discussed, as well as the types of fuel cells currently being pursued in industry. Next, a description of the fuel cells used at The Cooper Union in the past is presented. This shows some reasoning behind the acquisition of Proton Exchange Membrane fuel cells in recent years, as well as the desire for ambient-air breathing stacks. Subsequently, these types of fuel cells are detailed. Finally, a full description of the *BCS Technology* fuel cell stack is given.

2.1 Fuel Cell Operation and Classification

As described in Section 1.3, electrolysis splits water into its constituent parts of oxygen and hydrogen by introducing energy through an electrical current. It was Sir William Robert Grove who first demonstrated, with his "gas battery," by combining the two parts correctly electricity could be generated through a sort of reverse-electrolysis

[8]. The field has grown over time to include more techniques for the “correct” method of recombination, but the idea has remained the same. A fuel cell is a device that converts the chemical energy of a fuel and oxidant into low voltage direct current electricity, which can be immediately supplied to a load [5]. In this manner, and as suggested by the name of Grove’s device, the fuel cell is similar to a regular battery, which is an electrochemical cell (or a collection of cells) that produce a constant voltage current (or movement of electrons) .

Looking at how a battery accomplishes the energy conversion from chemical to electrical helps demonstrate how the process works within a fuel cell. Figure 2.1 shows a schematic of a primary battery.

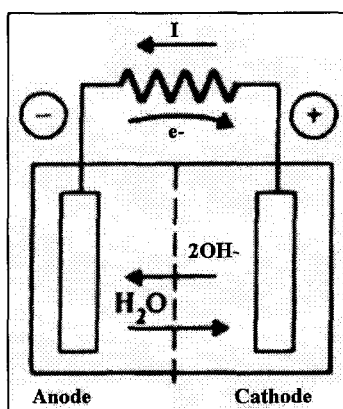


Figure 2.1: Diagram of a Typical Primary Battery [5]

Electrons are lost within the anode in an oxidation process to the external circuit and gained in the cathode for the reduction process. A typical mercury battery, for example, would have zinc at the anode which would gain two hydroxyl ions from the cathode to form zinc oxide, water and two free electrons. These electrons pass through the circuit performing the desired work, to the cathode, in this example mercury(II) oxide. The free electrons, along with the water found in oxidation, react to form mercury and the needed hydroxyl ions. The balanced process continues in this matter until all of

the zinc and mercury(II) oxide have reacted to form zinc oxide and mercury, at which point the battery is considered “dead” [10]. A secondary battery, such as the lead storage battery commonly found in an automobile, can be recharged by applying a current to reverse the oxidation-reduction reaction. However this requires the input of an outside electrical source, and the battery obviously can not be used during this “recharge.”

In contrast, the fuels are not stored internally in a fuel cell but rather continuously fed from an external source. As a result the reactions do not have to be reversible and there will be a constant flow of products out of the fuel cell, consistent with the conservation of mass. . Thus a fuel cell can be considered as a direct fuel converter and can in theory work indefinitely. This should be stressed as nothing trivial; the freedom for these reactions to continue without needing a follow-up reaction eliminates the need for erroneous substances forming unwanted compounds, thus the product formed is most often pure water, as will be explained later [2].

This freedom fathers a classification method between types of fuel cells; simply where the product is formed and then removed from the system. The intermediary products in a battery must be used to complete the counter-reaction, and have a definite direction of flow as is seen in Figure 2.1. Without this restriction these flows are not as definitive, and rely on the particular characteristics of the fuel cell. The first type of fuel cell, type A, is shown in Figure 2.2. This figure also lends itself well to a discussion on general fuel cell operation, as well as introduces the vital element of a fuel cell, the electrolyte.

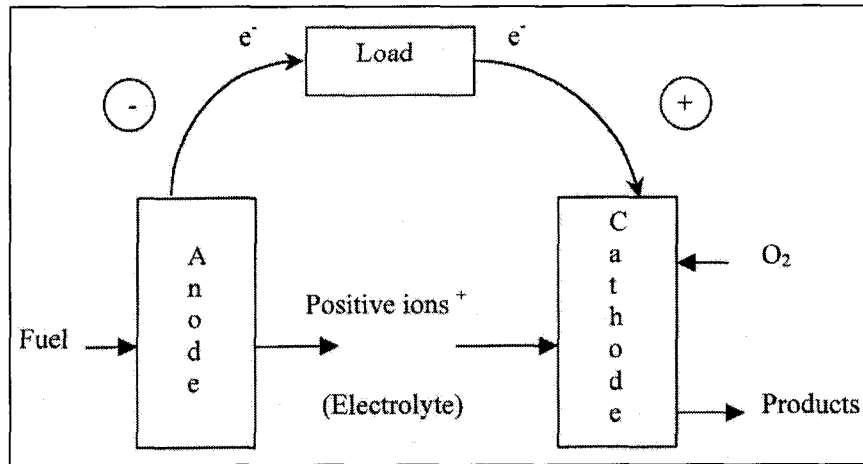


Figure 2.2: Diagram of the Flow within a Type A Fuel Cell [4]

The flows of the fuel and oxidant are not unique to this type, rather this is common for all fuel cells. The fuel is supplied at the anode and oxidizes and the oxidant is supplied at the cathode and reduces, and a current is generated moving electrons from the anode to the cathode to do work via a load. The energy of formation of the end product is the motive force behind this work [10]. What is unique to Type A is the generation of the product at the cathode. The electrolyte allows the positive ions of the oxidized fuel to travel to the cathode and restricts the freed electrons, forcing them to pass through the outside circuit. On the cathode side, using the electrons from the circuit the reduced oxidizer bonds with the positive ions that come through the electrolyte.

Type B has the opposite flow across the electrolyte, and is shown in Figure 2.3. Here the negative ions are allowed to pass through the electrolyte, and the product is formed at the anode. The final type of fuel cell, type C, has this direction of ion flow as well. However the electrolyte acts more as a mixing chamber. So while the negative ions flow over to the anode, the final product is collected at the cathode. These are the three types of fuel cells under this classification, but another classification of fuel cells is apparent from this discussion: the material of the electrolyte itself.

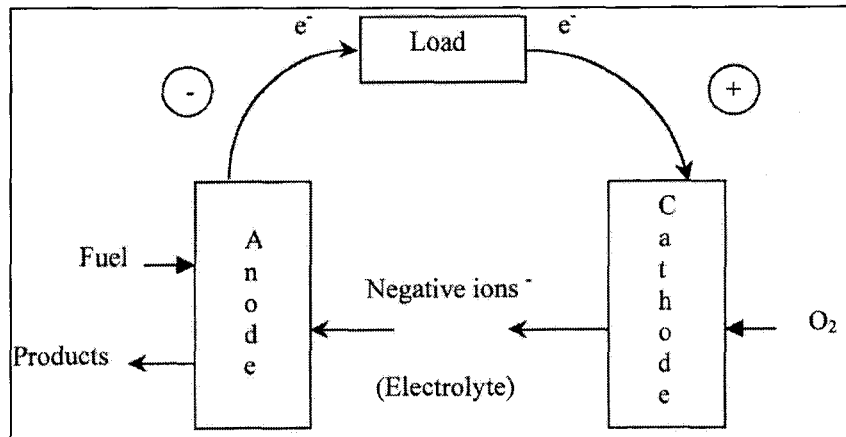


Figure 2.3: Diagram of the Flow within a Type B Fuel Cell [4]

The interactions of the electrodes and electrolyte determine operating properties of a fuel cell such as the maximum current and voltage it can achieve, its nominal operating temperature, and the type of fuel and oxidant that it works with. The electrolyte is also the main reactive agent and a description of this part of the fuel cell clearly represents its caustic or non-caustic nature, and thus types of applications most suitable. It is for these reasons that the electrolyte material is the primary characteristic used to classify fuel cells; for example, the name Molten Carbonate Fuel Cell is referring to the molten carbonate electrolyte. The properties of this electrolyte require the reactions within the fuel cell to happen at the higher temperature of about 600 degrees Celsius, and allow the use of natural gas directly as its fuel [11]. The former is the main disadvantage of the fuel cell, evident by “molten;” it does not lend to mobile applications well.

Much of the research of the field is focused around the goal of finding the right combinations of electrolyte properties for a given application, giving rise to many types of electrolytes. Some common electrolytes found in industry include phosphoric acid, solid oxide, direct alcohol, alkaline, and the proton exchange membrane.

The type of fuels and oxidants used define a third classification of fuel cells. The molten carbonate fuel cell is a natural gas - carbon dioxide fuel cell. The products that form from using natural gas are similar to the undesirable emissions that currently cause the environmental problems associated with combusting this fuel and the same is true for those fuel cells who can accept propane and gasoline directly [3]. Thus there is no environmental benefit over the combustion process other than the inherent higher efficiency, discussed below. The term “fuel cell” is so often related with the idea of clean energy because most are hydrogen-oxygen fuel cells, meaning they only use pure hydrogen at the anode, and pure oxygen in the cathode. Figure 2.4 shows this reaction in a type A fuel cell. Hydrogen enters the fuel cell at the anode and breaks down into hydrogen ions, which are simply protons. These pass through the electrolyte towards the cathode where they react with the reduced oxygen to form pure water. NASA uses this type of fuel cell to both power their crafts and to supply the drinking water for the astronauts [5].

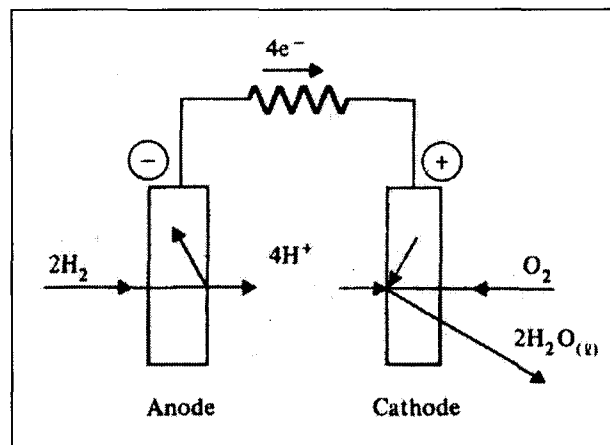


Figure 2.4: A Hydrogen-Oxygen Type A Fuel Cell [4]

The individual cell that is shown in Figure 2.4, and indeed for all types of fuel cells, are generally used in series with other identical cells in what is known as a fuel cell

stack. The name “fuel cell” is almost always interchangeable with “fuel cell stack” or “stack” as they are generally connected in stacks [2]. The source of the pure hydrogen needed for these hydrogen-oxygen stacks remains a problem. While hydrogen is the most abundant element in the universe, it is very rarely found unbound to some other element. The most common way of producing hydrogen gas is to extract it from hydrocarbons with a chemical refining process called “cracking,” however this process is accomplished with highly caustic compounds and results in similar harmful emissions associated with combustion [3]. Thus any hydrogen-oxygen fuel cell operating with “cracked” hydrogen is not operating cleanly on a global scale because harmful byproducts are produced, whether it be in a chemical plant or directly before entering the fuel cell in house.

Electrolysis requires at least the energy of formation of water to be supplied via an electrical source. Since this energy is the source of a fuel cells power, its output could only match the energy put into electrolyzing the water if there were no losses to the system, which are inevitable. So the questions are; where does the initial electricity come from, and why wouldn't it just be used directly, without the fuel cell, if the application is stationary? The StarFuel System answers these questions with the most environmentally friendly solution through photovoltaic electrolysis. Once pure hydrogen is produced from nothing but water and the inexhaustible, but varying supply of energy from the sun, the hydrogen-oxygen fuel cell can convert it back to pure water and a steady supply of electricity for stationary and mobile applications. Hence the title of the technology's patent, “Energy Conversion System” [1]. Only in this manner is fuel cell technology truly emission free.

If hydrogen is used in an internal combustion engine to produce energy, the combustion process would have the same zero emission quality of fuel cells, producing just water and heat. However combustion is an irreversible process governed by the second law of thermodynamics and the efficiency is bounded by the Carnot efficiency, equation 2.1. Here η_{\max} is the maximum efficiency, T_c the temperature of the cold reservoir (or ambient temperature), and T_h is the temperature of the hot reservoir (or combustion temperature.) The most efficient of internal combustion heat engines can only achieve efficiencies of 40 to 50% with most operating well below this [5].

$$\eta_{\max} = 1 - \frac{T_c}{T_h} \quad (2.1)$$

The fuel cell is not limited by this cycle because the chemical energy is harnessed without the use of moving parts or heat cycles in a relatively isothermal, semi-reversible, controlled process; the ideal efficiency for a hydrogen-oxygen fuel cell is 83.0% [5]. This is how the fuel cell dominates over heat engines environmentally and economically, by using less fuel to produce an equal energy output. For a full thermodynamic analysis of fuel cells, refer to Chapter 2 of Mr. Lomma's Master's Thesis, reference 5. For a detailed discussion on hydrogen as a fuel, including the history, advantages and disadvantages, and contemporary uses of hydrogen as a fuel, consult Chapter 2 of Chin's thesis, reference 4.

2.2 History of Fuel Cells at The Cooper Union

The Cooper Union had its introduction to fuel cells with the *Allis-Chalmers* 120-S potassium hydroxide (KOH) hydrogen-oxygen fuel cell test stand. The four-cell stack

had a power output of 120 Watts with a KOH concentration of 35% by weight and had an operating temperature of 200° F. The stand included pressure, flow and thermostatic controls, product water condenser, reservoir and pump, all of which are shown in Figure 2.5 along with the flow paths of the reactants.

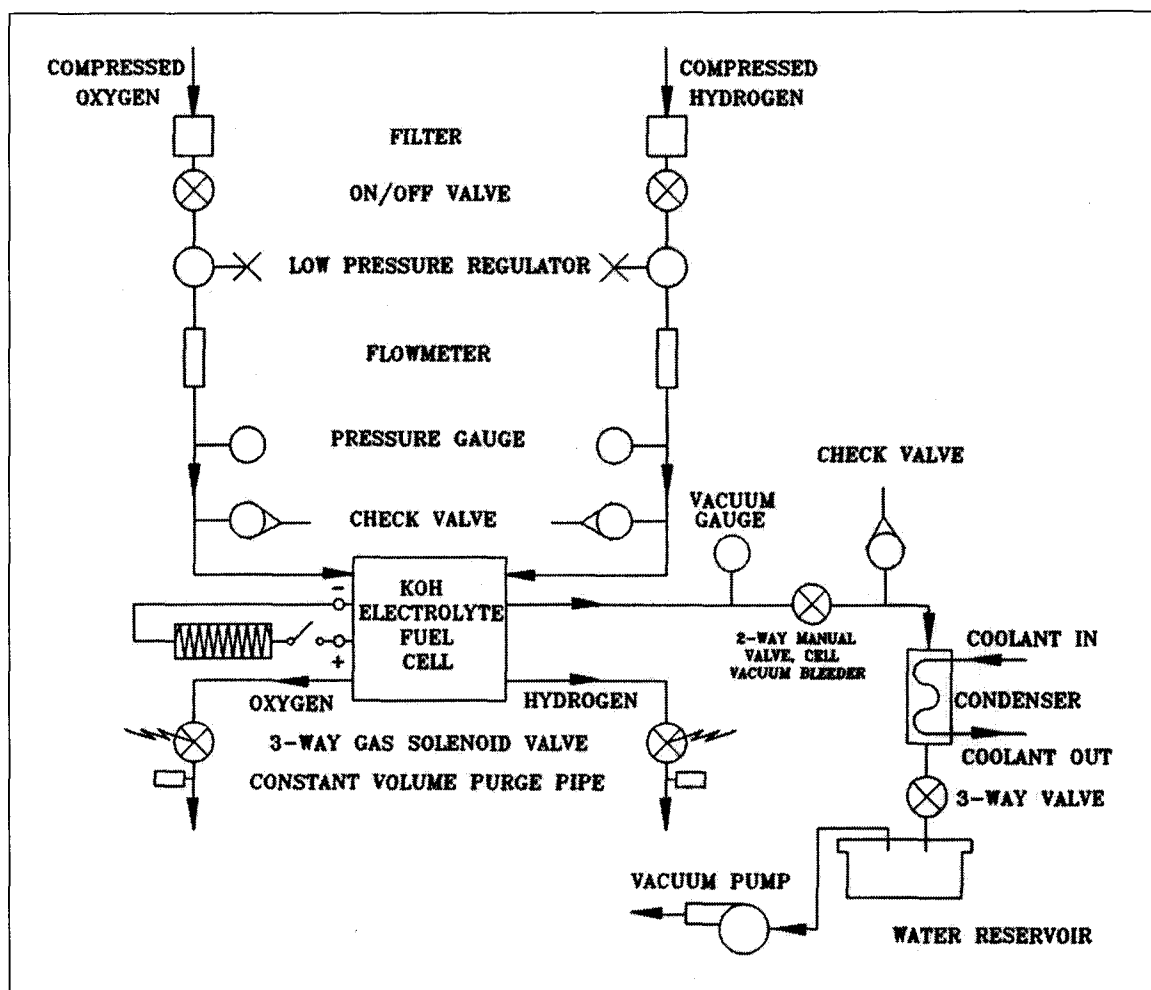
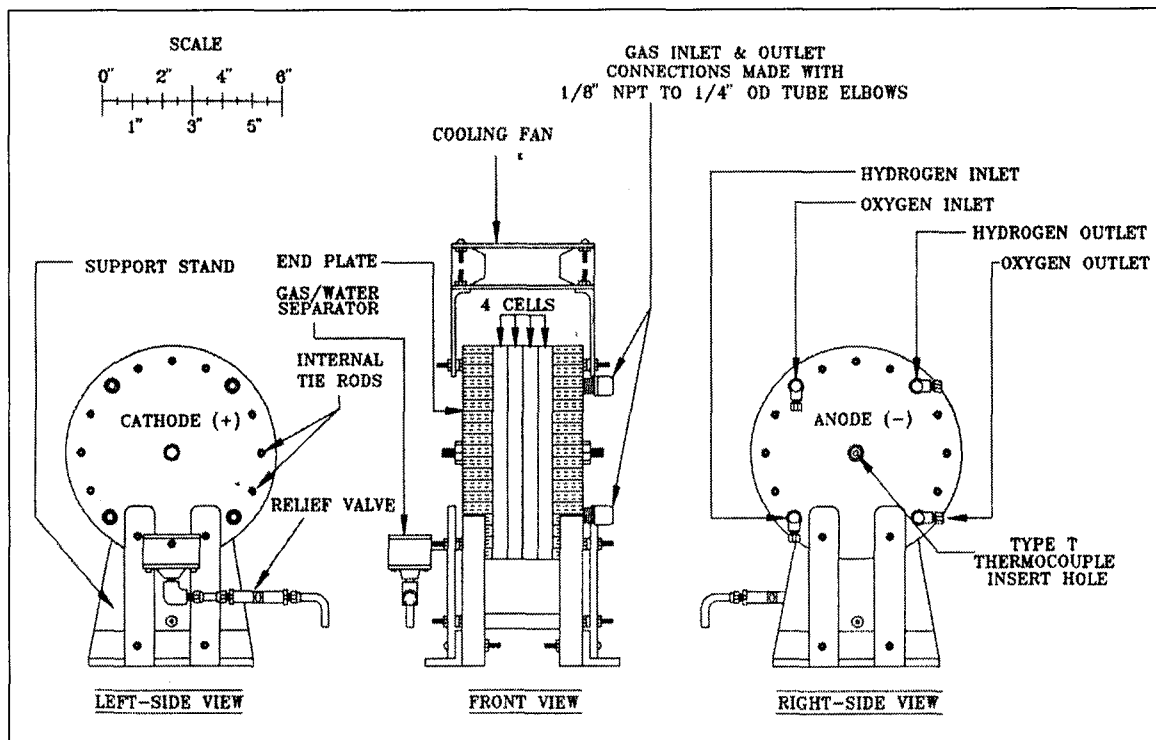


Figure 2.5: Schematic of reactant flow paths in the *Allis-Chalmers* fuel cell test stand. [taken from 7]

The stand was used for testing and demonstration from the early 1970's until 1983, when thorough testing exposed problems such as hydrogen leakage, cell dehydration, electrode corrosion, and electrolyte contamination. The search for a replacement stack began with the decision to look for a solid polymer electrolyte (SPE®)

as it was believed that eliminating the caustic materials from the test stand would result in a longer lasting, relatively maintenance free demonstration tool [5]

The replacement was never purchased and the test stand was discontinued from use, and it was not until about a decade later that another fuel cell found its way back into The Cooper Union. This was for the thesis work of Modroukas to establish the Hydrogen Utilization Module, as discussed in Section 1.6.1. After a full search, the *A.F. Sammer Corporation's* 130 Watt Proton Exchange Membrane, hydrogen-oxygen, 4-cell stack, model AFS 125-4 was leased for a term of one year, picked up on September 26, 1994 by Mr. Modroukas [7]. Figure 2.6 shows the details of the fuel cell configuration.



**Figure 2.6: The *A.F. Sammer* PEM cell configuration
[Taken from 7]**

This fuel cell required as a minimum ultra-high purity hydrogen and oxygen as its reactant gases. The HGM must produce hydrogen at this purity level to avoid contaminating the hydride tanks of the HSM, so the first requirement was a natural fit to the StarFuel System. As stated before, the second requirement was solved with a *Matheson* compressed oxygen tank. The operating properties of this stack are as follows: oxygen pressure of 30 psig, hydrogen pressure of 5-30 psig, nominal temperature of 70°C, and a maximum temperature of 80°C. The current produced was at maximum 50 amps, and ran continuously at 12.5 amps. For full details on this fuel cell stack, refer to Mr. Lomma's thesis, reference 5.

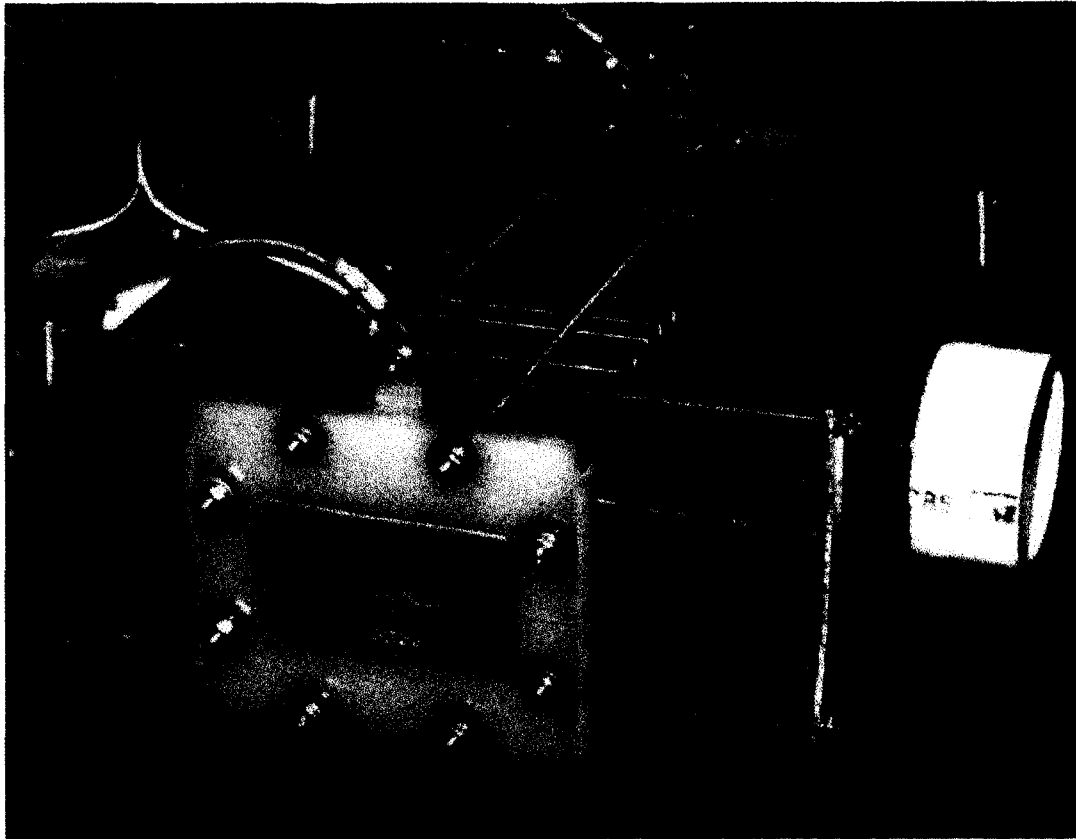
Over the few months that the test stand was being constructed, a carbonaceous matter was spotted in the oxygen inlet port of the stack, resulting in its return to the manufacturer for repair for an absence of three weeks. The stack was first supplied reactant gases while attached to a load on March 25, 1995. An internal fire developed after just minutes of connection, and after shutdown and purging similar carbonaceous matter found previously was noticed in the hydrogen inlet and outlet ports. The stack was once again returned to the manufacturer, this time for the extended period of over a year while extensive repairs were made. Lomma received the stack back on July 21, 1996 to complete his thesis work with the modifications mentioned earlier [5].

The stack was successfully supplied by the compressed hydrogen source briefly on March 21, 1997 while attached to a load. No data was reported from this short run. Two days later the stack was again supplied from the compressed hydrogen source for almost 200 minutes up to approximately 80 Watts while the MCDASM took data for

current, voltage, temperature, flowrate, and pressure at regular time intervals. The stack was then run for couple of more hours to allow it to “break in.” [5]

The *StarFuel System* was first run as a completely integrated system by Mr. Lomma on April 10, 1997, supplying steady power to a cassette player. The fuel cell was run for approximately 80 minutes supplied by the compressed hydrogen tank as tank #1 of the HSM was being charged by the HGM, powered by the PVM. The source of the HUM was then changed from the compressed hydrogen tank to the HSM, with tank #2 discharging and the load was switched to the cassette player, with a total system output of approximately 45 Watts. After about 40 minutes of operation from tank #2, a manual switchover was performed to use the hydrogen being produced and stored in tank #1. Data was collected from all four modules by the MCDASM allowing for many studies, such as the power and flowrate response for all systems [5]. Additional runs were performed before this stack was returned to the manufacturer in the summer of '97.

With the problems encountered from the hydrogen-oxygen fuel cell, it was desired to remove the need for the research oxygen with the replacement. This design specification was met with the acquisition of the *H Power* PEM 30-cell hydrogen-ambient air fuel cell stack by Chin in 2000. The stack is shown in Figure 2.7, and required hydrogen of 99.95% purity, industrial grade, and took the oxygen it needed directly out of the ambient air with a built in fan assembly (the white tube on the right of the photo is the air exit). The hydrogen pressure inlet requirement was between 3 to 5 psig and the nominal temperature range was between 45° to 48°C.



**Figure 2.7: Photograph of the *H Power* Hydrogen-Air PEM Fuel Cell
[Taken from 4]**

Hydrogen was first supplied to the *H Power* stack through the HUM from the compressed hydrogen tank on March 21, 2000 to a small load, outputting 5-10 Watts for about a half hour. Again on March 28, 2000 from the compressed tank, with an output reaching 20 Watts (varying load) over a two hour run. On April 3, 2000 the fuel cell was supplied hydrogen for the first time by hydride tank #1 of the HSM for over two hours at a power of 5 Watts, and on April 4th from tank #2 at 15 Watts for approximately one and a quarter hours. The stack was returned to *H Power* over the summer of 2000.

2.3 The Proton Exchange Membrane (PEM) Fuel Cell

The proton exchange membrane is a solid polymer electrolyte typically constructed with sulfonic acid groups chemically bonded to a fluorocarbon polymer

backbone (such as Teflon). The acid groups allow hydrogen ions (protons) to transfer from the cathode across the surface of the membrane to the anode, classifying the PEM as a type A electrolyte. The composition of the membrane is always in solid phase and does not change, requiring much less maintenance and providing for much safer operation than other electrolytes that use molten or caustic liquids. Adding to its safety and ease of use are the low operating temperatures of typically less than 80°C [5].

These fuel cells have a high power output per unit of cross-sectional area of the cell, or power density, and typically have high power output to weight ratios. The low pressures and temperatures, along with its solid state allow for nearly silent operation and they accept only hydrogen as a fuel to produce only water and heat, making them the most environmentally friendly fuel cells available [4].

2.4 The Ambient Air Breathing Fuel Cell

The hydrogen-oxygen fuel cell is supplied its oxidant with a closed, controlled oxygen line, fed directly into the cathode and then internally dispersed to individual cells by the inlet pressure. Generally this oxygen must be ultra-high purity because of the danger of contaminants building within this direct feed leading to the possibility of a combustible mixture (obviously very dangerous around a pure oxygen source) or the contamination of the electrolyte.

The ambient air breathing fuel cell, i.e. the hydrogen-air fuel cell, eliminates the need for a direct oxygen feed by providing air channels directly into each cell. The oxygen is removed from this air much like the human lung achieves this, utilizing osmosis. The cell must have some humidity around it to start the process, and using the water within the air the oxygen is passed into the electrolyte. After some time (dependent

on the type of cell and ambient humidity) enough water is produced from the hydrogen-oxygen reaction within the cell to cover the cathode with a thin film, furthering the transfer rate of oxygen. Thus these cells are “self-humidifying”. To help with this process, sometimes water is directly added to the cells at startup [9].

The rate of transfer is not only dependent on the humidity of the cell, but the availability of the oxygen within the air. If there is no movement of air at the reaction sites the oxygen will be depleted and the cell will be unable to perform its reduction, thus prohibiting its ability to perform. If the air is moving, but too slowly to bring in enough oxygen to fully supply the needs of the cell, performance drops. Thus there needs to be a continuous circulation of air fast enough to supply the needs of the cells throughout and around the stack. This is achieved with two methods: forced and natural convection. The first is directly controllable with the use of a fan to move the air throughout the stack; the more power delivered to the fan, the faster the air can be moved. Note that it is possible to overpower the fan because the cells have a limit to the oxygen supply needed, which is important because the power used to run the stack decreases the net power output of the fuel cell. Natural convection increases as the temperature of the stack increases. The air immediately around the stack is heated by it, and then rises away bringing cooler air to continue this process cyclically. If the temperature gradient between the ambient air and the stack increases, the heat transfer increases and this process occurs faster. The time it takes to humidify the cells and achieve nominal operating temperature is the start-up time of these fuel cells. Before this time the stack is unable to perform at its maximum.

To provide the channels in the stack that the cells to “breathe” the electrolyte used is generally a PEM because of its solid form. However there is also an additional, and

important reason that air breathing stacks use this membrane. By taking the oxygen they create nitrogen-rich air as a product, and as just discussed this air is heated. If the stack was running at temperature associated with other electrolytes the nitrogen could bond with oxygen once mixed with outside air, forming harmful oxides. With the PEM, the air leaves the stack at relatively low temperatures, avoiding this negative affect [4].

2.5 Description of the *BCS Technology* 10 Watt PEM Fuel Cell Stack

As stated above, Hobden et al. were looking for a Proton Exchange Membrane, ambient-air breathing fuel cell stack with no moving parts as the *H Power* stack's replacement. They found the *BCS Technology* 10 Watt PEM Fuel Cell, shown in Figure 2.8, was the only available model on the market that matched these requirements.

It is a 10-cell hydrogen-air, self-humidified fuel cell stack that relies entirely on the natural convection of air for the movement of oxidant into the membrane sites, eliminating the need for a fan. The fuel required is industrial grade hydrogen, not the ultra-high purity hydrogen that has been the requirement of past stacks. At maximum conditions the stacks runs at 5 VDC and 2 amperages with a input flow requirement of less than 200 standard cubic centimeters per minute (sccm), determined experimentally by the manufacturer. The maximum allowable pressure input is 2 psig and the maximum operating temperature is 70 degrees Celsius.

According to the manufacturer, the electrical output of the fuel cell is directly related to the mass flow rate entering the stack, and it is this flow that must be altered to be more or less for a higher or lower demand from the load, respectively. The pressure of the inlet hydrogen is of little concern to the reaction process, but must be kept under 2

psig to avoid damaging the membrane [9]. The manufacturer found the required flows for hydrogen inputted at two states: at exactly the rate of consumption defined as a stoichiometry of 1.0 and at a rate higher than the fuel cell would use, a stoichiometry of 1.1. The table of experimental results from the manufacturer is shown in Table 2.1. It is recommended that the stack be run at the second rate for maximum performance, however this will result in the unused hydrogen gas exiting with the product water at the cathode. The total amount unused can be calculated simply by subtracting actual flow with the flow necessary at 1.0 stoichiometry. For example, the stack’s recommended flow input for 1.5 amps is 104.4 ml/min. This will result in 9.5 standard milliliters of hydrogen unused every minute of operation. The flows for the 1.0 stoichiometry were found using the stack “dead-ended.” This and normal operating procedures can be found along with other manufacturer comments in Appendix B, the manufacturer’s accompanying documentation.

Table 2.1: Stoichiometry chart for hydrogen flows in (ml/min)

Hydrogen Stoichiometry	Current (A)							
	0.2	0.5	0.7	1.0	1.2	1.5	1.8	2.0
1.0	12.6	31.6	44.3	63.3	75.9	94.9	113.9	126.6
1.1	13.9	34.7	48.7	69.6	83.5	104.4	125.3	139.3

To extract the excess hydrogen from the product water, the manufacturer has suggested a water trap. The device can be as simple as a flask plugged up with a cork that has an inlet hole and an outlet hole (this is what they use at *BCS Technology*) [9]. The gas exiting the water trap will be mostly hydrogen, however there will be some water vapor contamination. It is perfectly acceptable to feed this hydrogen back into another stack’s inlet, however there will not be enough flow to run another stack solely with this.

As a result, the manufacturer recommends venting the unused hydrogen after collecting the product water [9].

The manufacturer has also recommended a design for the stand that the stack must rest on, and has provided a “shade” that fits over the top of the stack. The two of these are related because they are designed to help increase the convection around the stack, allowing the needed oxygen to get to the reaction sites faster, thus increasing performance. As stated in the documentation, the performance will not reach its peak until about 15 minutes of operation.

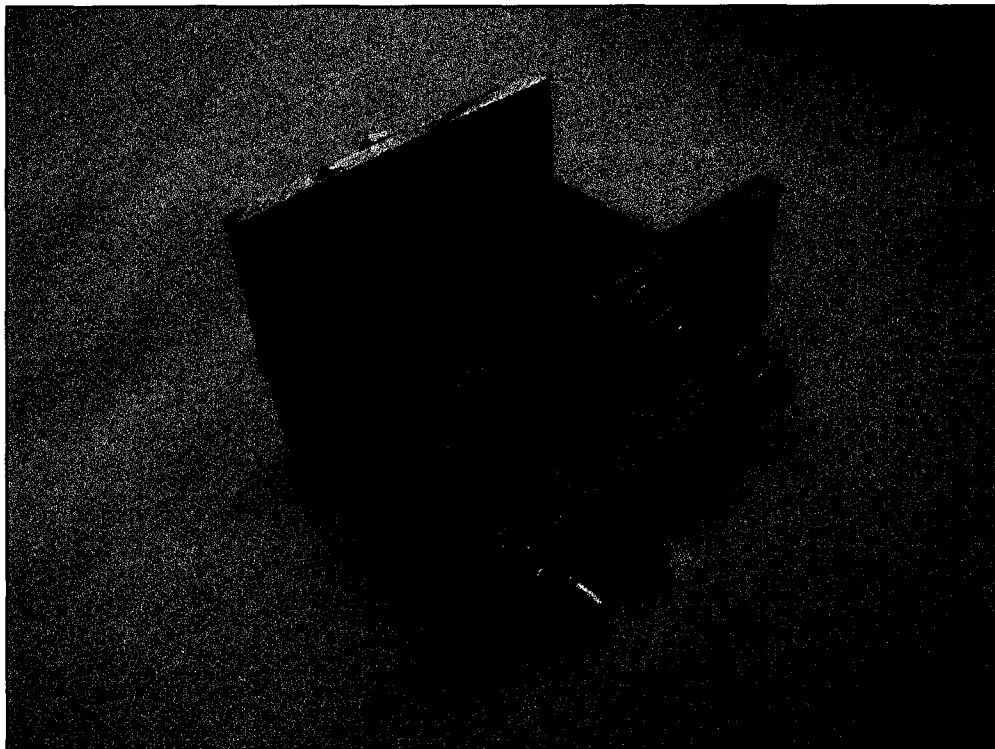


Figure 2.8: The *BCS Technology* 10 Watt Fuel Cell Stack

Chapter 3: Revisions for the Hydrogen Utilization Module

This chapter will discuss the changes that are necessary for the installation of the three *BCS Technology* fuel cells into the Hydrogen Utilization Module, as well as describe in detail why each change is needed. While the installation is the direct result of this work, the objective is not simply to replace the *H Power* 30 Watt fuel cell that was on loan with the three 10 Watt stacks that are now owned by The Cooper Union. The HUM is a useful test stand that exists for the study of this emerging technology as much as it exists to complete the StarFuel System's original concept. Having the ability to test three fuel cell stacks working together considerably increases the module's range as a fuel cell test stand, with the possibility of gathering transitional data between running one, two, to all three stacks supplying a varying load.

3.1 General Design Overview

The design parameters can be broken down into five main objectives:

- 1) Install three *BCS Technology* fuel cells and all of the equipment necessary for controlling and measuring the pressure and flow independently into each stack,
- 2) House all of this new equipment entirely within the existing HUM,
- 3) Make the test stand easy to use,
- 4) Allow for future integration into the MCDASM for total centralized system control, and
- 5) Keep any equipment that may be useful for, as well as allow for flexibility in implementing other fuel cell stacks in future projects.

As the original design focused around the needs of the fuel cell it supplied as the main design criteria, so must this design focus around the new stacks' requirements in the same manner. The most obvious and important difference of this stack to the other two stacks previously used with the HUM is its requirement for a high sensitivity of control and monitoring at low mass flows and low pressures. As stated in the documentation, the stacks operating current is dependent directly to the inlet flow, running between 0 and 200 sccm, and the maximum allowable inlet pressure is 2 psig.

The nitrogen service was installed by Lomma to clean the test stand and the fuel cell from any contaminants as the stack needed ultra-high purity hydrogen for operation, as well as to help avoid leaving the potentially explosive mixture of oxygen and hydrogen at any point [5]. However, since the oxygen service will be removed from the stand there is no longer a possibility of this mixture. Additionally, the new fuel cells require only industrial grade hydrogen for operation, so the few contaminants that could find its way into the system (for instance, from construction) will not do any harm, or cause any operational fluctuations with these new stacks. Thus the nitrogen service is also no longer necessary and will not be incorporated into the flow design of these stacks, however the existing system will be left for the possibility of incorporating this feature for future fuel cells.

To make room for the new equipment to fit within the existing module, the air-breathing quality of the stack can be capitalized on by removing the oxygen flow equipment from the stand. As stated in Section 2.4, the state of the art is leaning towards the hydrogen-air fuel cell stacks with the reasoning that they do not require the dangerous element of pure compressed oxygen, nor the added expense of delivering it. Therefore it

is unlikely that the HUM will ever need to accommodate a stack with this feature, allowing for its removal without prejudice.

The hydrogen equipment that is shown in this figure is for a higher pressure and flow than needed for this application. However there is no need to remove this equipment, as there is ample space for the revisions and it increases the capacity of the module to have the ability to deliver at these higher levels for future applications. Additionally, this equipment will add as an additional pressure stage for the control of delivery to the new system between the high pressure outputs of the HSM, as will be explained in detail below. Thus the new equipment will be installed directly downstream of the pressure transducer (item 36).

3.2 The Importance of Materials

Referring to Section 1.5, the hydrogen that is produced by the HSM is stored in a solid state utilizing metal hydrides. This is to say that there is reactivity between hydrogen and certain metal alloys that changes them into these hydrides. Within a hydride tank that is housed correctly and contains available metal powder this reaction is welcomed. However outside of these systems another way to phrase the reaction is the hydrogen attacks the metal, corroding it into a metal hydride. This is exactly what would happen if the wrong materials were used for surfaces the hydrogen contacts directly, including the piping that the gas travels through, as well as any internal parts of control valves and monitoring equipment, and the seals between connecting components. Over time the hydrogen would corrode the parts to the point where they no longer work properly, and eventually lead to the much more dangerous problem of a leak.

Rather than list all of the alloys that hydrogen is reactive with, or all of the alloys that hydrogen is safe to use with, the materials commonly used in controlled fluid flow systems are eliminated or accepted. The seven main materials are aluminum, bronze, brass, 303, 316 and 321 stainless steel, and Monel (a ceramic). These are also listed in order of increasing cost [13]. The objective is to find the material that fits the application at the lowest price. While piping and other components can be manufactured with a material other than these main materials, they are more expensive and thus of little interest to this design. The first three materials listed are highly reactive with hydrogen and thus are unacceptable. The last is a ceramic and has no reactivity with hydrogen, however it is rather expensive.

Stainless steel is the main material used throughout the StarFuel System, specifically 316. Every internal part that comes in contact with the hydrogen gas from every valve to every fitting is 316 stainless steel, with the exception of some plastic piping that is used in the ventilation system. Following this precedent, and because it is the least expensive, and most available material for accomplishing this task, 316 stainless steel is used throughout this design.

3.3 Monitoring and Controlling the Hydrogen's Mass Flow Rate

BCS Technology has only one requirement for the control of these fuel cell stacks to match a given load, and that is precision mass flow (as shown in the connection diagram that came with the stacks). Specifically high precision for the low mass flow between zero ccm, shut off, to 300 ccm of fully open. This requires equipment that can monitor low hydrogen flow rates with a high resolution to know more accurately what is

happening, and valve equipment with a high sensitivity in low ranges for the control itself.

3.3.1 The Rotameter and Gas Needle Valve

There are two main types of flow monitoring devices, analog flowmeters and digital flowmeters. The most common form of the analog flowmeter is simple, so its relatively inexpensive, precise, and can be calibrated to be very accurate for low flow rates: the rotameter. It works by utilizing the variable area principle as is shown in greater detail in Figure 3.1. The three components of the rotameter are a float, a tapered flow tube, and a measurement scale calibrated for the specific fluid the device is being used for, at a specific pressure and temperature. The flow tube is situated vertically with the smaller side, the inlet, at the bottom. The float is a sphere with a diameter matching that of the inlet diameter of the flow tube, which is completely seated when there is no flow. When fluid is introduced, the float is lifted from its seat, allowing the fluid to pass by in the larger diameter flow tube. As more fluid moves through the device, more room to pass is needed, and the float rises up the tube to the corresponding diameter that fills this need. Known flow rates are used to calibrate the meter's measurement scale. [14]

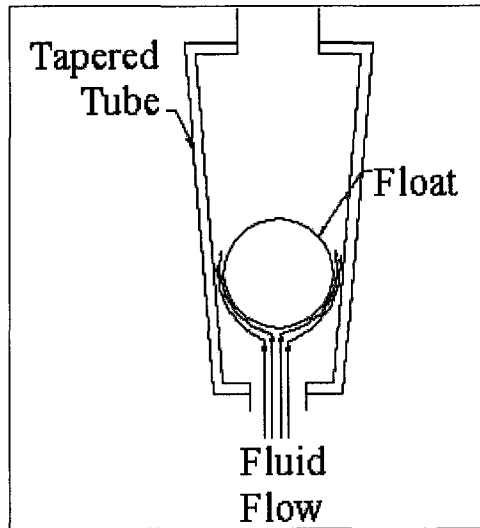


Figure 3.1: Principles of the Rotameter

The rotameter can be changed to measure small to large flow rates with two basic modifications. By altering the taper of the flow tube and the size of the float, different displacements of the float can be achieved for the same flow rates. If it is desired to measure low flows, for example, a smaller taper will cause the float to move higher up the device with an equal flow, thus increasing the sensitivity, and decreasing the range if the length of the tube remains constant. The second method is to change the density of the float itself. A less dense float will rise quicker than a denser float, causing the same effect to sensitivity and range.

The fluid's temperature, pressure, and specific gravity affect a rotameter's measurement of flow. While the latter is a constant for a given fluid, the former two demand that the meter be used in similar operating conditions that it was configured for. Different ratios of output to input pressures cause the float to move at different increments, thus giving an inaccurate measurement if used in a different manner [14]. This does put a restriction on the range of pressures within a rotameter can accurately

measure flow rate. However, with the low pressures of this system the rotameter can deliver accurate flow measurements for hydrogen and is a cheap and viable option.

With the addition of a high precision gas needle valve at the inlet, a rotameter can become a flow-controlling device. These valves are designed to work within definite flow ranges, defined by the particular design requirements. Fully open valves allow the upper flow limit through, and fully closed restrict the flow to the minimum (usually no flow). The valves generally have a set number of turns they can make between the two limits, so the higher the range the lower the sensitivity. The properties of the control change with different fluids (as the rotameter does) but they do not need to be calibrated for use with different fluids or at different pressures. What results from a large pressure change is a change in flow rate at a particular setting of the valve, and this change must be manually adjusted for.

3.3.2 *Digital Mass Flow Meters and Mass Flow Controllers*

The alternative to the analog rotameter is the digital flowmeter. This device uses a transducer that produces a voltage proportional to the flow it is measuring. A control box that has been calibrated for the type of fluid being measured then interprets this voltage and gives a digital readout for the user. Since the specific gravity of a fluid is unique and relatively independent of pressure and temperature, the flow rate can be measured by detecting the rate of heat transport within a defined area of the gas stream without concern for these variables [14]. How the actual measurement of the heat transport is accomplished varies between companies and is a source of intellectual

property arguments (patent issues). What is most important though is that these devices can be used with large temperature and pressure differentials with great accuracy [13].

Having the possibility of these large differentials, the StarFuel System takes advantage of these devices in the HGM, HSM, and HUM for measuring flow rate. The additional advantage to digital flow meters spawns from the computer-ready nature of the device itself. Since the mass flow rates have already been turned into electrical signals, a computer data acquisition board can input the information directly from the controller box. The flows in these three modules are measured with these devices only, so while the computer records the information continuously the instantaneous reading is displayed for the user on the display box. These meters have high accuracy associated with them as well, with an error of $\pm 1\%$ of full scale. The scale is determined by the application, and can be focused in on a particular range. [13]

Digital flow meters give birth to the possibility of digital flow control. The interactions between these two also differ between manufacturers, and although it is somewhat premature to reason why this unit will be used for this work, the *Matheson Model 8270 Mass Flow Controller System* will be detailed to further this discussion. The unit uses an electronically linked control valve to control the flow, which is a modification of a high precision gas needle valve. The valve works in the same manner as discussed above, but an electronic motor turns the control knob automatically rather than by the user manually. This is accomplished with a simple closed loop control system, shown in Figure 3.2.

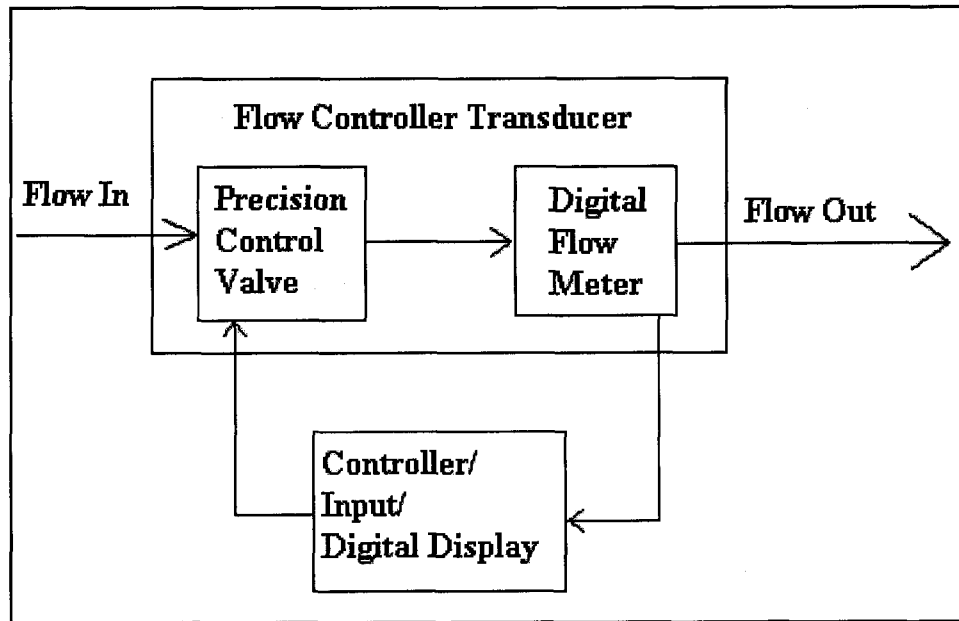


Figure 3.2: Closed-Loop Control System used in Mass Flow Controller System

The display box of the flowmeter system is replaced with the control box, and the transducer used for simply measuring flow is incorporated into a single unit with the control valve (Model 8273 flow controller transducer) [14]. The user inputs into the controller box via keypad the desired flow rate. Then the box sends a signal to the motor of the control valve to start the flow. This flow is read by the transducer and interpreted by the control box. If the flow is greater than or less than the user set flow rate, the controller sends a signal to the control valve to close or open more, respectively. This is done at a rate of 60 Hz, or 60 updates per second. Thus any change in temperature or pressure that would have effect on the flow is automatically accounted for by the automatic controller system and results in a higher degree of precision by removing the human element, and adding to the ease of use (objective three).

The added benefit of this system compliments the fourth objective of the design, the future integration with the MCDASM. This box can be directly connected to a data acquisition board and controlled remotely though this connection from a computer [13].

Finally, there will be no need to replace the flow control for future fuel cell applications that might require larger pressures, benefiting the fifth design objective. As a consequence this technology is built into the design over the manual rotameter-valve assembly.

Since it is desirable to have control into all three of the fuel cells, three such flow controller transducers are used together with one *Matheson* 8274 Series Multiple Mass Flow Controller Box. This unit has one display, but can simultaneously control up to four such transducers (leaving room for any future expansion) [14]. A Series 8124 Totalizer can compute the total hydrogen used by one, two, or all three fuel cells over time, regardless of varying flow rates. This option is only desirable for a system that has not been connected to the MCDASM, as this module could easily do this calculation with the collected data. However since this module is not included in this design, the Totalizer is kept as a suggestion.

Finally, as these units are included in the final design, it is necessary to discuss an important effect these controllers have on the pressure of the system. Due to the internal workings of the flow controller transducers, there must be a pressure differential between the output of the controller and the input, specifically a loss in pressure from inlet to outlet. Matheson withheld the details of this, however they remarked that they could design the controller to deliver a specific pressure reduction as low as 3 psi to eliminate variable, or unknown pressures within the stream [13]. This is discussed further in Section 3.5.

3.4 Manifold Design

To change from the one flow of hydrogen currently available to the three independent flows needed a fluid manifold is necessary. In theory, a source of variable pressure can be delivered to unlimited outputs at either that pressure or less using variable area outputs on a fluid manifold. The basic concept is similar to creating a small gas tank, which is supplied by one source at some pressure. The output of this tank has pressure valves that vary the area used for flow, thus limiting or increasing this pressure. A mass flow that is greater at one output will need this valve to be closed more than the other outputs to keep all output pressures equal.

A custom manifold for this design is a redundant task because this is needed so often in fluid control that there are many off-the-shelf parts available, and this lowers the cost. A *Matheson* GasTrak Delivery System is made from stainless steel by standard, and has the option of up to four outputs. The model for this application is L0300S3-32.

3.5 Pressure Control and Monitoring

The pressure considerations for the design are focused around the need to lower the delivery pressure of the test stand to the pressure needed at the inlet of the flow controllers, and limit the inlet pressure of the fuel cells to 2 psig. From this comes the need for precise measurement within this low pressure in the interest of data acquisition.

3.5.1 Pressure Delivery Control

The pressure regulators used to control delivery from the HSM to the HUM and again for delivery to the fuel cell and are rated for 4 to 150 psig. They work by reducing a high pressure source to a lower, user-set pressure. The inlet pressure can change however there are some transient effects on the outlet pressure over one reduction, a single stage regulator. Dual stage regulators use two pressure reductions, the first to bring the pressure down to roughly three times the maximum outlet pressure and the second to the desired level, minimizing these effects. Two single stage regulators in series achieve this goal as well, which is one reason for the regulators used in the StarFuel system to be single stage.

Regulators are made for a wide range of pressure distributions and sensitivities, and can be used in this application. Since it will be placed directly downstream of the existing regulator, a single stage regulator is all that is needed to supply an unvarying pressure. There are a great deal regulators that are rated to work with such a small range, however they contain unacceptable materials. The lowest pressure stainless steel regulator available has a delivery pressure between 0 and 30 psig, which can be lowered with the use of a substantially more expensive custom regulator [13]. The off-the-shelf

regulator is acceptable for this application because, one, the fuel cells do not require control of the pressure but limitation for operation, and two, future fuel cells may require pressures slightly higher, which eliminates the expense of a custom part.

The *Matheson* single-stage high-purity stainless steel regulator, model 3571-CGA, capable of delivering hydrogen from 0-30 psig fulfils all the design requirements. This regulator is included prior to the manifold for the simultaneous limitation of pressure to all three supply lines, avoiding the excess expense of three without eliminating any necessary control.

During operation, the pressure regulator will be set at a maximum of 2 psig plus the constant pressure differential across the mass flow controller.

3.5.2 Pressure Delivery Limitation

The membranes of the fuel cell can be damaged if the let pressure is higher than 2 psig. As a precautionary measure, some limiting device must be installed in case this pressure is exceeded for whatever reason. The simplest, and cheapest solution for this is the installation of a relief valve. The maximum is pre-set in these valves and if their inlet pressure exceeds it the flow is vented out of the piping assembly. They are made with some audible warning that they have tripped, and are easily reset. This is acceptable only if the valve is placed directly downstream from a quick shut-off valve, and if the system is only run with an operator present to do so. The former is included in the design, and the latter is already a standard operating procedure of the StarFuel System.

3.5.3 Pressure Measurement

Similar to mass flow measurement, pressure is measured with analog and digital devices. The StarFuel System uses both of these methods throughout for automatic and manual data acquisition, and the ability to compare both for any inaccuracies. Generally, the precision of digital devices is much higher than analog.

As with regulators, low pressure analog gauges constructed with stainless steel are available with custom construction alone [13]. The regulator is desired for the precision measurement of inlet pressure, which is designed to be no greater than 2 psi. Since off-the-shelf ranges are unacceptable, the analog regulator is eliminated in interests of conserving on cost.

Thus, digital pressure gauges will be used. A pressure transducer is installed within the fluid flow that outputs a voltage proportional to maximum pressure the system is rated for. The pressure compresses a piezoelectric cell within the transducer which produces the voltage that is interpreted by an output display. These devices can work in a large or small range applications and can be built with varying sensitivities. The transducers used are *Matheson* Model MTRN-NEW connected to a panel mounted process monitor that is capable of outputting to the MCDASM, Model 8571-001.

3.6 Product Considerations

As discussed in Section 2.5, the water that is produced will be accompanied with unused hydrogen and water vapor. For the ability to continuously run this system without regard to the outputs of the fuel cells, the water must be separated from the gas and discarded into the New York City sewage system, and the gas ventilated in the

existing system. This is a simple process with the utilization of a water trap, as suggested by the manufacturer. The goal is to keep the design of this trap simple, but upgrade from using just a beaker and a cork to allow for continuous use without having to manually dispose of the product water when the beaker is filled.

Figure 3.3 shows this simple design. The outputs from the three fuel cells are fed into a container with tubes that are below the water line. The hydrogen gas will rise to the top of the container and exit through the hydrogen out, which is attached to the existing ventilation system of the HUM. The excess water will spill over into the next trap that will keep the hydrogen from exiting down into the sewage system, similar to the trap toilets use to prevent gasses from coming up from the sewage system. Since this setup will be permanent and the water is pure, a valve is included for the option of collecting the water instead of disposing of it. This option also allows for the measurement of the product water in a graduated cylinder.

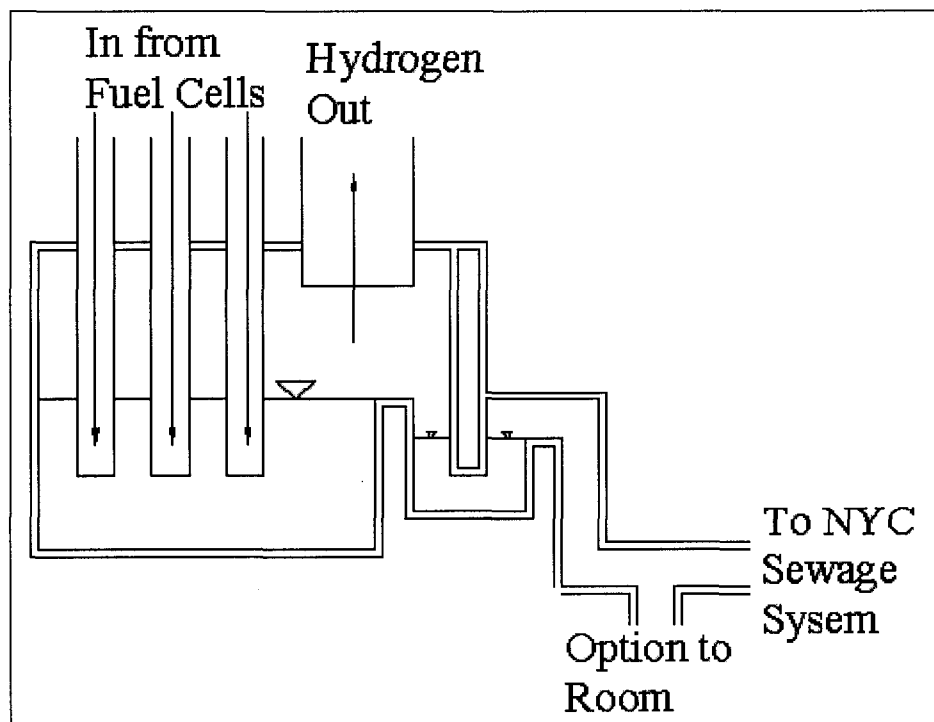


Figure 3.3: The Water Trap

3.6 Details of the Final Design

Figure 3.4 is the schematic diagram of the layout for the equipment to be added to the HUM for clarity of hydrogen line flow as a summary to the previous sections of this chapter. After the pressure transducer that is currently in place, the hydrogen precedes to the *Matheson* Model 3571-CGA stainless steel single-stage high-purity miniature regulator. This regulator will deliver a low pressure to the *Matheson* GasTrak™ Delivery System which splits the hydrogen line to deliver to all three fuel cells simultaneously. This unit has the necessary valves for turning on and off the flow into each fuel cell and is the first of two such controls.

The three lines all contain the same equipment for each identical fuel cell. First the *Matheson* Model 8273 flow controller transducer controls the flow rate of hydrogen, directed by the 8274 Series Multiple Mass Flow Controller Box. This box is where the user sets the desired flow rate and monitors each with a digital readout. The hydrogen proceeds to the pressure transducer, Model MTRN-NEW for the final measurement of inlet pressure to the fuel cells, and this is read off of the monitoring device, Model 8571-001 (three in total.)

A check valve (*Matheson* Model 401V) is included after the previous two units, instead of after the manifold, to prevent the possibility of any product water or vapor being sucked back into the system causing damage to these units. Next is the final valve for user control for convenience and to facilitate quickly halting flow to the stacks during an emergency or any other reason, a diaphragm packless quarter-turn valve, *Matheson* model 4360. The last component before the connection to the fuel cell is a pressure relief valve, which will automatically release the pressure from the line if it gets to this stage

above 2 psig to ensure the fuel cells do not get damaged. After each fuel cell the products are carried to the water trap for disposal.

All of the equipment have been chosen and configured together to serve the objectives of the design in order of major importance. First and foremost, the three stacks can be safely operated within their intended operating parameters and the necessary degree of control has been achieved. As a result, the transition for future use of other fuel cells that are similar to the *BCS Technology* fuel cell stack will require no change in this set-up, however there have been some things included in the design that will need replacement or removal, such as the pressure relief valve, for higher pressure and flows. These components make up a small part of the system, and are relatively inexpensive compared to the control equipment and manifold system.

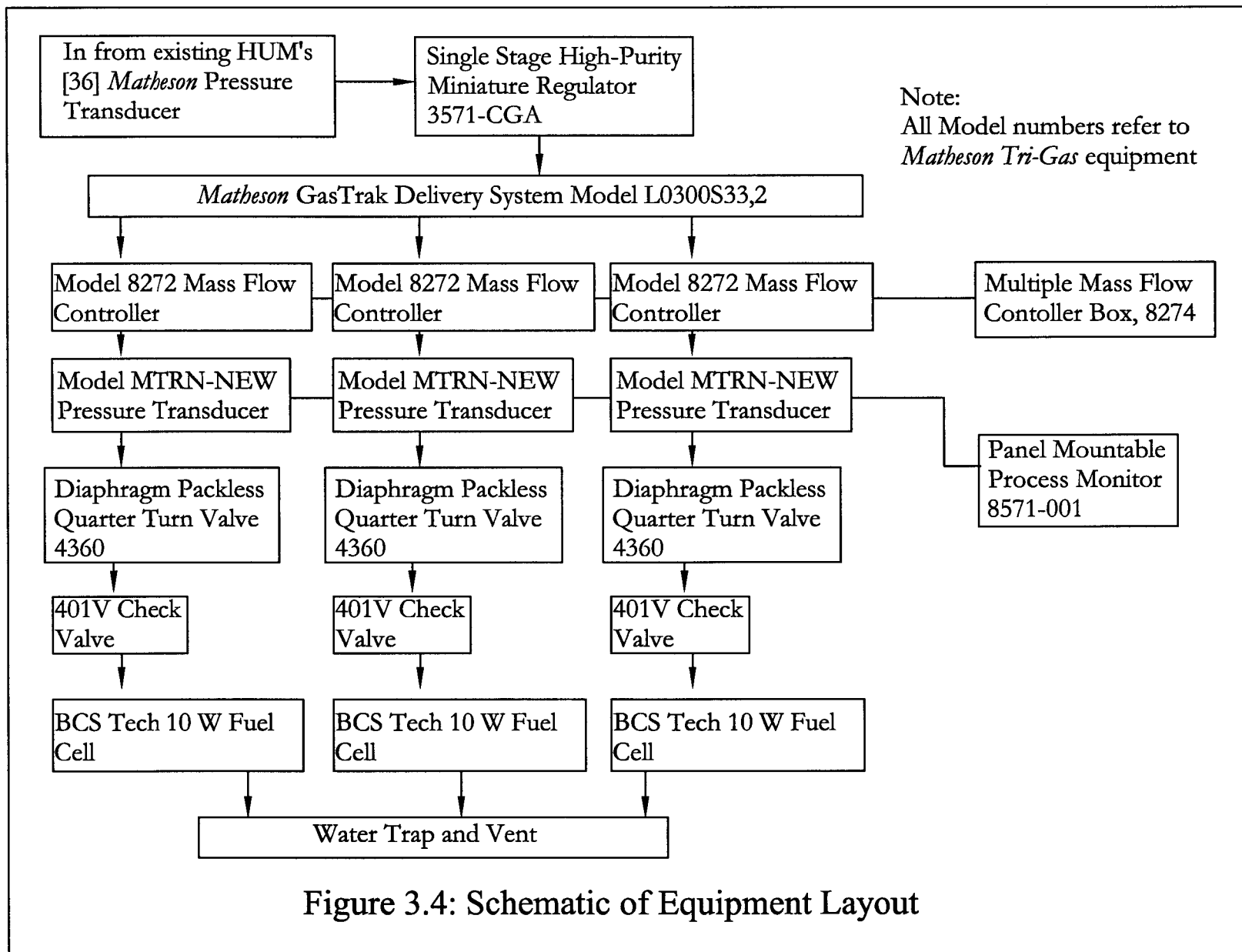


Figure 3.4: Schematic of Equipment Layout

The final design drawings are shown on the next two pages: Figure 3.5 shows the a front view of the new HUM, and Figure 3.6 shows the back with the piping layout and placement of all of the components

The layout has been designed for ease of use, following the natural progression of hydrogen flow that is consistent throughout the StarFuel System. Looking at the system, the HGM and HSM are on the left of the HUM, likewise the compressed hydrogen tank. The hydrogen enters the HUM in the back on the right, and the equipment that was kept flows from the top of the unit towards the bottom on the right side of the test stand. With the oxygen service removed, the left side of the test stand is free to accept the control equipment for the three stacks. The GasTrak controls are placed on the top of the three columns of delivery piping at eye level. The mass flow controller is placed directly under the GasTrak system for monitoring and controlling the flow to each line. Each pressure monitor is placed in the panel over the location of the stacks on the bench. The quarter-turn valves are not located on the panel but rather directly before the stacks on the bench to give easy access to each, and the pressure relief valves are directly after these.

Stack #1 is placed on the right side of the bench, and its piping runs down left of the existing hydrogen lines, after the GasTrak, behind the panel. Stack #2 is placed in the center of the table, with controls behind it, left of #1, and stack #3 to the left of that. The stacks are placed on the manufacturer recommended stands and separated from each other to allow for maximum airflow around each. If they are placed to close to each other they could suffocate. The products are fed back behind the test stand's face to the water trap that is placed on the side of the HUM, where it is easily connected to the existing

hydrogen vent. The lines are kept angled down at all times to prevent backflow of product water into the stacks, and thus the trap is at around knee height.

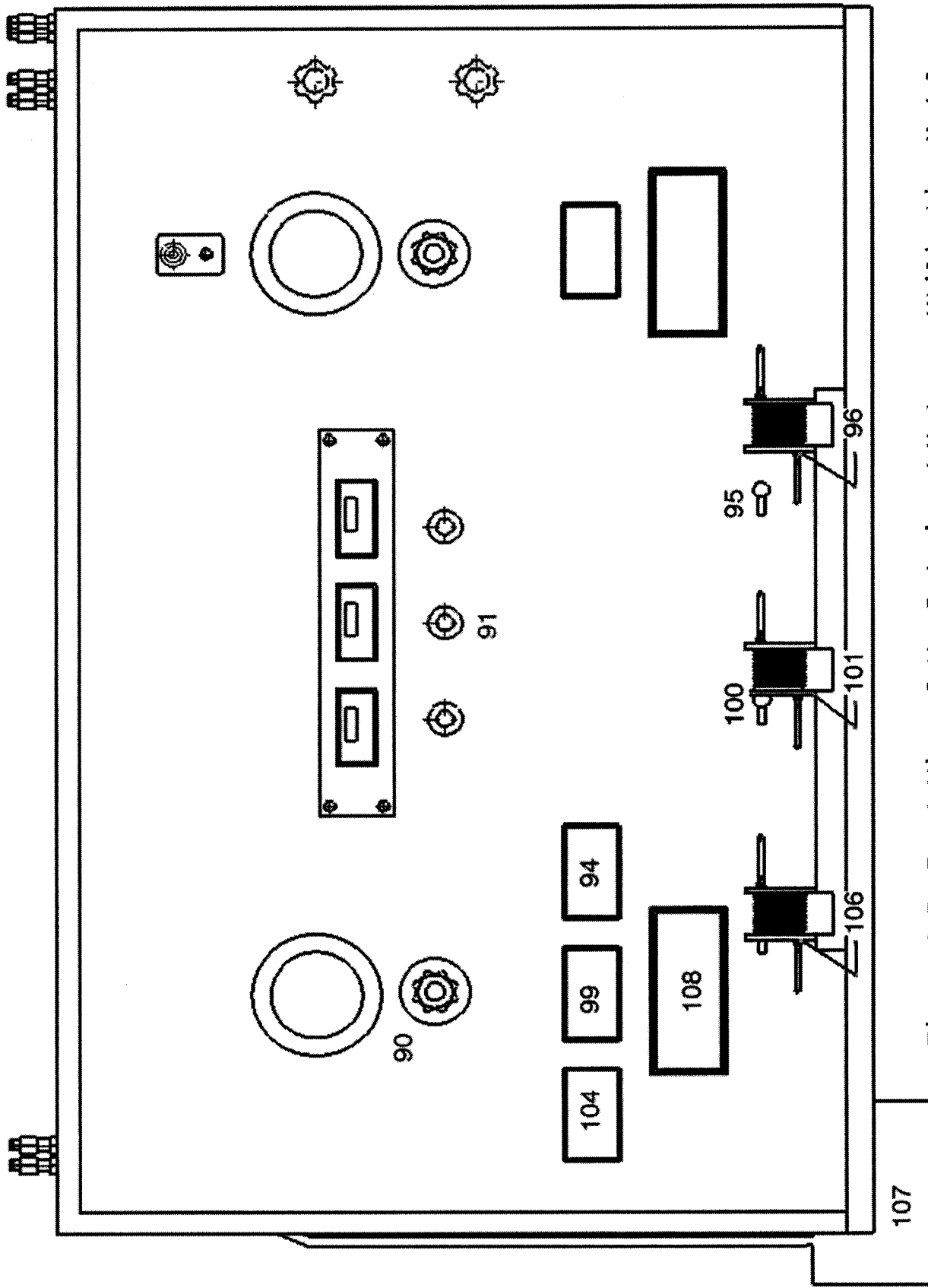


Figure 3.5: Front View of the Redesigned Hydrogen Utilization Module
 Scale: 1 inch = 1/2 foot

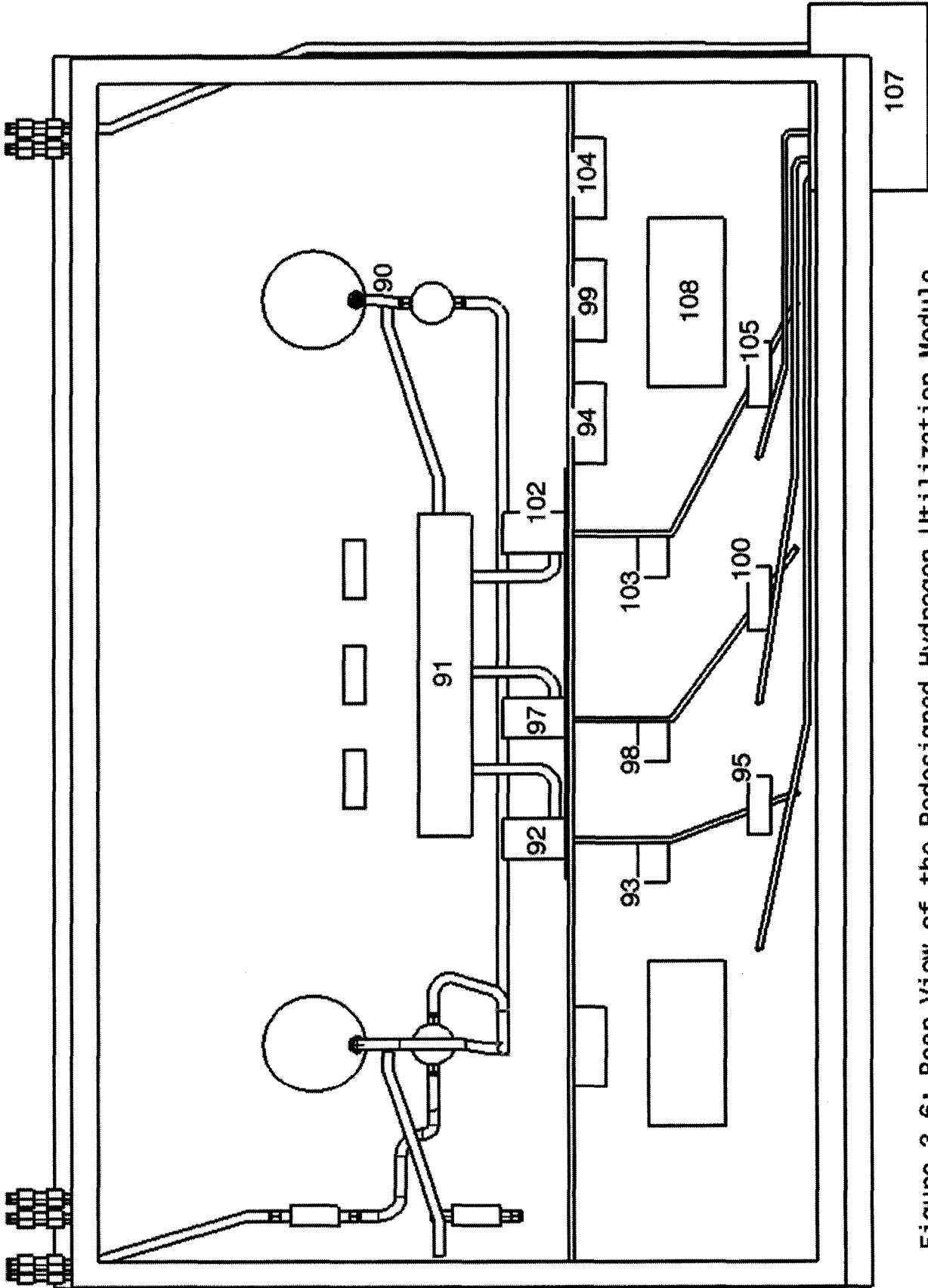


Figure 3.6: Rear View of the Redesigned Hydrogen Utilization Module
 Scale: 1 inch = 1/2 foot

Table 3.1: New Components for the Hydrogen Utilization Module

90	<i>Matheson</i> Model 3571-CGA single stage high purity miniature regulator
91	<i>Matheson</i> Model L0300S33,2 GasTrak delivery system
92	<i>Matheson</i> Model 8272 mass flow controller calibrated for hydrogen service
93	<i>Matheson</i> Model MTRN-NEW pressure transducer calibrated from hydrogen service
94	<i>Matheson</i> Model 8571-001 panel mountable process monitor
95	<i>Matheson</i> 4360 Series diaphragm packless quarter turn valve
96	<i>BCS Technology</i> 10 Watt hydrogen-air fuel cell stack
97	<i>Matheson</i> Model 8272 mass flow controller calibrated for hydrogen service
98	<i>Matheson</i> Model MTRN-NEW pressure transducer calibrated from hydrogen service
99	<i>Matheson</i> Model 8571-001 panel mountable process monitor
100	<i>Matheson</i> 4360 Series diaphragm packless quarter turn valve
101	<i>BCS Technology</i> 10 Watt hydrogen-air fuel cell stack
102	<i>Matheson</i> Model 8272 mass flow controller calibrated for hydrogen service
103	<i>Matheson</i> Model MTRN-NEW pressure transducer calibrated from hydrogen service
104	<i>Matheson</i> Model 8571-001 panel mountable process monitor
105	<i>Matheson</i> 4360 Series diaphragm packless quarter turn valve
106	<i>BCS Technology</i> 10 Watt hydrogen-air fuel cell stack
107	Water Trap of Figure 3.3
108	<i>Matheson</i> 8274 Series multiple mass flow controller box calibrated for hydrogen gas service

Chapter 4: Summary and Recommendations for Future Work

With the implementation of this design the StarFuel System will once again be a fully operational solar-hydrogen energy conversion system, capable of supporting an electrical load of up to a reliable 30 Watts of power through three *BCS Technology* 10 Watt PEM fuel cells. This addition will also include the ability to monitor and control the fuel cells' operating conditions, providing for the addition of computer control and data acquisition. Thus the StarFuel System will also include a useful research test station for the study of multiple fuel cells supplying a variable load.

The design parameter of no moving parts adhered to by the rest of the system is made possible here by the main components about which the test stack is designed around, the ambient-air breathing convection stacks purchased and awaiting installation. The equipment for the supply of these stacks has been chosen from *Matheson Tri-Gas*, whose components are used throughout the StarFuel System, and their cost estimate of the major elements is included in Appendix B.

As any author of a needed design would, it is recommended that this project be physically built into the StarFuel System when the funds become available. While the cost estimate will have to be re-quoted by the manufacturer with additional items, it includes the major costs and provides a sense for the final price tag's range.

After the Hydrogen Utilization Module is returned to operational status, additional work on the Master Control and Data Acquisition Module would benefit the system as a research tool. This module does not have the capacity to include all of the control and data acquisition for the HUM as it is currently configured, needing additional data acquisition boards, as well as a total system upgrade.

Finally, as was suggested by Mr. Lomma in his thesis of 1997, the additions made to the system since the 3rd edition of the StarFuel Manual, along with the changes proposed for the HUM in this work, more than call for a new edition to be made. The current edition can not be followed for the safe operation of any of the modules without reference to more than one graduate thesis, defeating its purpose.

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Appendix A: *BCS Technology's* 10-Watt PEM Fuel Cell Manual

BCS Technology, Inc.
2812 Finfeather Road, Bryan, Texas 77801, USA
Tel. 979-823-7138 Fax: 979-823-8475
E-Mail: bcstech@txcyber.com

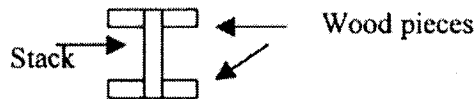
Guidelines for Operation of 10-cell 10W convection stack (S/N. 10-10-15R) and 16R

There are 10 cells in this stack. This is a self-humidified fuel cell stack. This stack does not require any humidification of reactants. This stack can be also operated dead-ended in hydrogen. Please refer to page 2₃ of this guideline for dead-ended operation.

This stack has been extensively tested for performance and gas leaks within the stack specifications at the laboratory of BCS Technology, Inc. It has been found to be running satisfactorily. We have collected the representative data. The performance should improve with time for some time.

The purity of hydrogen can be of industrial grade. The stack is started initially at the room temperature. It is not necessary to cool the stack to room temperature for subsequent start-up.

1. Place the fuel cell stack on two pieces of wood/plastic of at least one inch (2.5 cm) in height.



The schematic positions of the wood pieces and the stack are shown above. Make sure the wood pieces do not block the convection channels.

2. Cooling fans are not needed for this stack.
3. The connection of the stack to the hydrogen source should be made with a precision flow control valve. Hydrogen stoichiometry can be in the range 1.1-1.2. A bubbler can be used to see the hydrogen flow. When hydrogen is stopped, or the amount of hydrogen is insufficient at a certain current, water can be sucked into the stack. **This should be avoided.** No damage will occur for a momentary entry of water into the stack. If the water stays for a prolonged time, the cells can get damaged. An intermediate trap for water should be placed. The preferred connection is through a water trap (see attached figure).

A precision flow control valve is one, which is able to control precisely the hydrogen flow. Without a fine control valve, it may be difficult to pass the required amount of hydrogen to the fuel cell. (Alternatively, one can experiment with whatever control valve one has, and see if that particular valve is able to control the required hydrogen flow.) If one can set the flow in such a way that about 1-10 bubbles come in every second, that will be sufficient to run the stack.

If water trap is not immediately available, the end of the tube coming out of the hydrogen outlet can be submerged in water in a beaker or glass to see the hydrogen bubbles. However, the end of the tube must not be kept inside the water all the time, only when it is necessary to check the hydrogen flow. When the stack is operating, it is advisable to remove the end

of the tube from the water. It is a safeguard to prevent any unintentional transfer of water into the stack.

4. Pass hydrogen for 5-10 seconds. Initially, start the stack with a current output of 0.5A or less. Inlet hydrogen pressure of 0-1 psi may be required. If starting stack after a long time, distilled water can be sprinkled to facilitate quick current pickup (optional). If water is sprinkled, remove any water drops from air channels by blowing from the mouth. Also, wipe water from the bottom of the stack.
5. Put a shade (provided with the stack) around the top of the stack. The shade stabilizes the convection. A shade can be made from a slightly thicker paper of about 10 cm wide and enough length to encircle the stack.
6. Allow stack operation at 0.5-0.6A for 10-15 minutes before increasing the current further. This is to allow the temperature of the stack go higher. At a higher temperature, better convection occurs.

The current can be increased slowly making sure that the stack is able to sustain that current. This will depend primarily on the stack temperature and air movement in the surrounding. The full power can be obtained at about 50-55°C.

7. Put a thermocouple into one of the air-breathing holes in the middle of the stack to measure temperature. A digital thermometer comes with a convenient thermocouple for temperature measurements. Caution should be exercised while inserting a thermocouple into an air-breathing hole. The temperature measurement is not essential for operation of this stack.
8. Do not operate stack unattended until its characteristics have been understood.
9. Any blockage (partial or full) of channels by water drops can be removed by blowing. Blow occasionally from the mouth through the convection channels to remove any water accumulation. Water accumulation at the convection channels should clear up at a higher temperature.
10. After stack operation, it is advisable to pass hydrogen for a few seconds at a slightly increased flow rate to remove any water accumulated in the hydrogen flow channels.

STACK PROTECTION

- When the stack is not in use cover up with a plastic.
- Protect the air-breathing holes from blockage by any items.

Stack Specifications

Number of cells: 10, Electrode area: 10 cm², Reactants: H₂ /air and Reformate/air, Mode of H₂ flow: parallel, Mode of air flow: convection, Torque on bolts: 35 inch.pound, Power output: 10 W, Max operating temperature: 70°C. Operating pressure: 0-2 psi hydrogen.

Dead-Ended Hydrogen Operation

It is strongly recommended that, if the person operating the stack is not familiar with fuel cell operations, should first run the stack in the flow mode as outlined above. Some experience is required to run the stack at the dead-ended position.

Initially operate the stack for about 10-15 minutes under flow conditions before dead-ending hydrogen. Use a sensitive pressure gauge to monitor the pressure of hydrogen inside the stack. The pressure inside the stack should be within 2 psi.

To achieve dead-ended position, put a flexible 1/8 inch ID tube of length about 6-12" at the hydrogen outlet, and bend the tube holding it with a alligator or a similar clip.

Keep inlet pressure of hydrogen within 2 psi or as low as possible. Open the inlet valve sufficiently for the entry of hydrogen into the fuel cell stack.

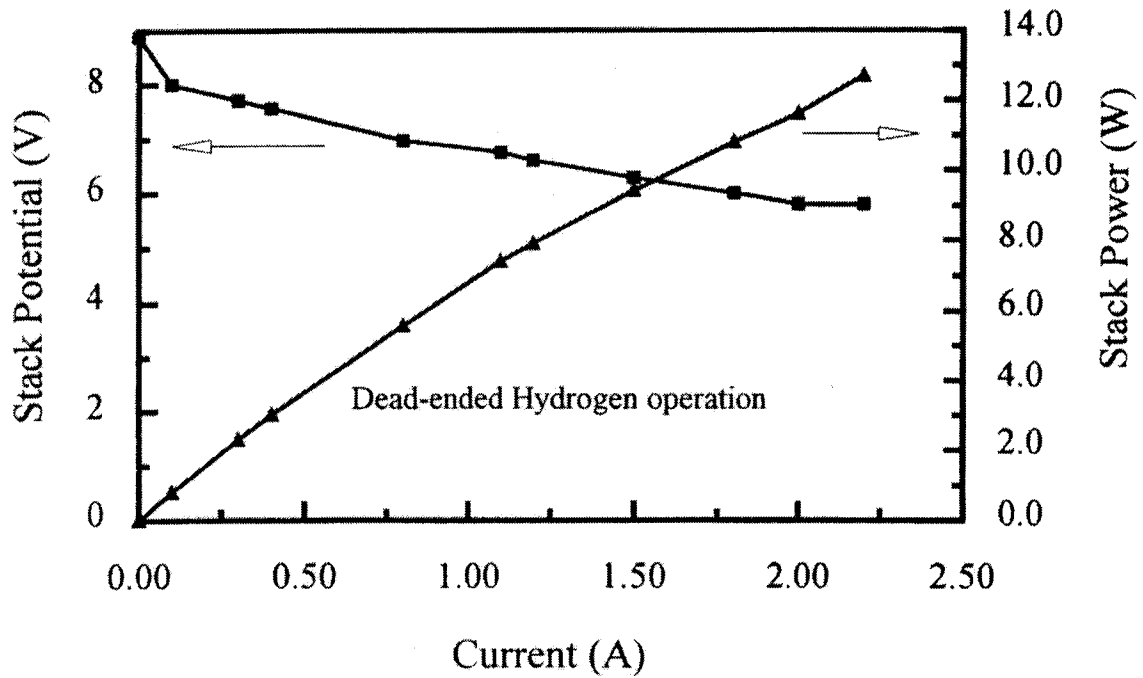
Every 1-3 minutes, the stack needs to be vented for about 0.5 to 1 second to remove any accumulated water.

Stoichiometry chart for hydrogen flows (ml/min) for 10-cell 10W stack

	Current (A)							
H stoich	0.2	0.5	0.7	1.0	1.2	1.5	1.8	2.0
1.0	12.6	31.6	44.3	63.3	75.9	94.9	113.9	126.6
1.1	13.9	34.7	48.7	69.6	83.5	104.4	125.3	139.3

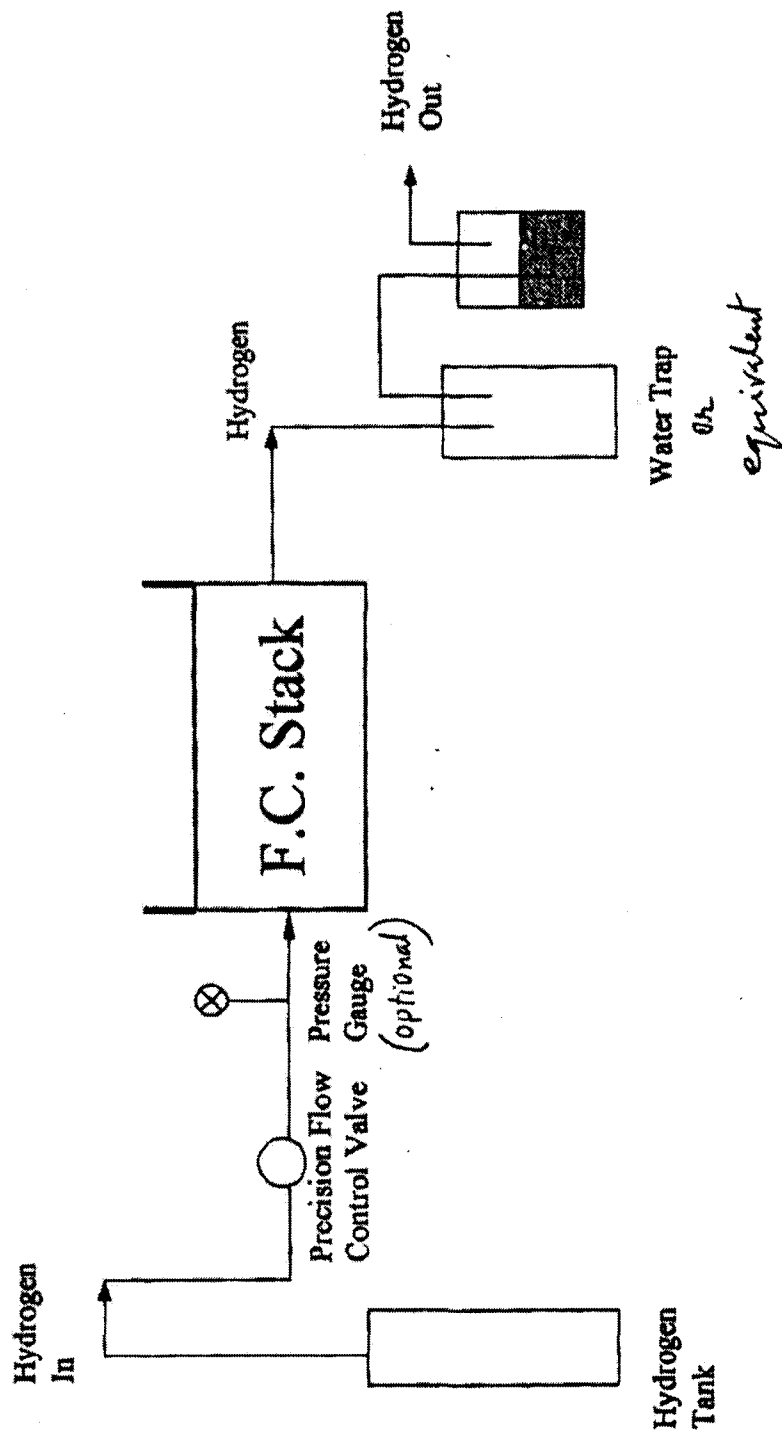
Please Note: The stack should not be opened. The performance may drop. Leaks may develop. If opening of the stack is needed, please send the stack back to us.

Performance data of 10-cell 10W stack



Reactants: Hydrogen/Air
Air flow by convection
T: 52°C
P: Hydrogen about 1.5 psi

Connection Diagram of Fuel Cell Stack



Appendix B: Equipment Quote from *Matheson Tri-Gas*



MATHESON TRI-GAS

166 Keystone Drive
Montgomeryville, PA 18936
Phone: (215) 641-2700
Fax: (215) 641-2714

Quotation No.: **03-108**

CUSTOM PRODUCT QUOTATION

Date: 3/24/03

Company: Cooper Union
Address: 51 Astor Place
New York, NY 10003

Contact: Griffin Reilly
Phone: 917-991-6019
Fax:
email: reilly@cooper.edu

RFQ#/Ref.:

MTG Rep.: John Smickenbecker

Line	Qty.	Model No.	Description	Unit Price	Ext'd Price
1	3	M8272-0452	Mass Flow Controller for H2, 0-500 sccm See note 2.	\$1,670	\$5,010
2	1	M8274	Multiple Channel Mass Flow Controller System	\$2,377	\$2,377
3	3	M8124	Model 8124 Totalizer	\$1,342	\$4,026
4	3	MTRN-NEW	Transducer, low pressure	\$314	\$942
5	3	MFF4364A	Diaphragm Packless Valve, 1/4 Turn	\$247	\$741

Total:	\$13,096
---------------	-----------------

Notes: 1) Installation, Plumbing, Electrical and Start-Up by Others.
2) Inlet and outlet pressure information required at time of order.

Delivery: 3 - 4 weeks after receipt of order

Terms: A finance charge of 1.5% per month is added to all past due amounts

F.O.B.: Factory - Montgomeryville, PA USA

Matheson terms and conditions of sale, including the warranty and limitation of liability, are an integral part of this quotation.

Quotation Valid: 30 Days from issue

Form: QT-form.xls 7/11/01

Authorization Signature
John Smickenbecker

Appendix C: Full Description of the Hydrogen Utilization Module's Current Equipment

The following list corresponds with Figure 1.5 on page 12, and is a full list of all of the equipment that currently comprises the Hydrogen Utilization Module.

1	<i>Matheson</i> Model SP-1197 one cylinder cone top gas cabinet for hydrogen
2	<i>Matheson</i> Model PAN-4005 3-valve analytical panel (delivery pressure 100 psig for hydrogen service)
3	<i>Matheson</i> Model 3510 series single stage high purity 316 SS regulator (4-100 psig)
4	<i>Matheson</i> 4364 series diaphragm packless process valve V1 for hydrogen service
5	<i>Matheson</i> 4364 series diaphragm packless isolation valve V2 for hydrogen service
6	<i>Matheson</i> 4364 series diaphragm packless vent valve V3 for hydrogen service
7	<i>Matheson</i> pressure relief valve
8	<i>Matheson</i> vent check valve
9	<i>Matheson</i> compressed research purity hydrogen size 1A (99.9999% min purity)
10	<i>Matheson</i> Model 6043-CGA 350 stainless steel flexible hose for size 1A hydrogen
11	<i>Matheson</i> compressed hydrogen cylinder valve/handwheel
12	<i>Matheson</i> series 6104 316 SS flash arrestor for hydrogen service (0-50 psig rating)
13	<i>Swagelok</i> SS-400-61 bulkhead union for compressed gas vent to hydrogen vent bulkhead
14	OD 316 SS tubing from compressed process hydrogen cabinet to fuel cell test stand
15	<i>Matheson</i> Model SP-1197 one cylinder cone top gas cabinet for oxygen
16	<i>Matheson</i> Model PAN-4005 3-valve analytical panel (delivery pressure 100 psig for oxygen service)
17	<i>Matheson</i> Model 3510 series single stage high purity 316 SS regulator (4-100 psig)
18	<i>Matheson</i> 4364 series diaphragm packless process valve V1 for oxygen service
19	<i>Matheson</i> 4364 series diaphragm packless isolation valve V2 for oxygen service
20	<i>Matheson</i> 4364 series diaphragm packless vent valve V3 for oxygen service
21	<i>Matheson</i> pressure relief valve
22	<i>Matheson</i> vent check valve
23	Removed April 2000, research purity oxygen tank
24	<i>Matheson</i> Model 6043-CGA 350 stainless steel flexible hose for size 1A oxygen
25	<i>Matheson</i> compressed oxygen cylinder valve/handwheel
26	<i>Matheson</i> series 6104 316 SS flash arrestor for oxygen service (0-50 psig rating)
27	<i>Swagelok</i> SS-400-61 bulkhead union for compressed gas vent to oxygen vent
28	OD 316 SS tubing from compressed process hydrogen cabinet to fuel cell test stand

Fuel Cell Test Stand

29	On/Off switch and LED assembly for process hydrogen solenoid valve
30	<i>ASCO</i> Model 8262-G86 12VDC hydrogen process solenoid valve
31	<i>Omega Engineering</i> Model PGT-45B-150 Pressure Gauge (0-150 psig)
32	<i>Matheson</i> 4374 series diaphragm packless manual backup hydrogen process valve
33	<i>Matheson</i> Model 3423, 4-100 psig single-stage high purity panel mount regulator

34	<i>Matheson 4374 series diaphragm packless hydrogen purge valve</i>
35	<i>Matheson Model 4183-2505 HA3 316 SS high accuracy hydrogen gas needle valve (0-2 slpm)</i>
36	<i>Matheson Model 8805 316 SS pressure transducer for hydrogen gas (0-115 psia)</i>
37	<i>Matheson Model 8571-001 panel mountable process monitor/controller (4-20 mA output option)</i>
38	<i>Matheson 8170 Series mass flow meter calibrated for hydrogen service (0-200 sccm)</i>
39	<i>Matheson 8170 Series mass flow display box calibrated for hydrogen (0-200 sccm)</i>
40	<i>On/Off switch and LED assembly for process oxygen solenoid valve</i>
41	<i>ASCO Model 8262-G86-N 12VDC process solenoid valve cleaned for oxygen service</i>
42	<i>Omega Engineering Model PGT-45B-150 Pressure Gauge (0-150 psig) cleaned for oxygen service</i>
43	<i>Matheson 4374 series diaphragm packless manual backup oxygen process valve</i>
44	<i>Matheson Model 3423, 4-100 psig single-stage high purity panel mount regulator</i>
45	<i>Matheson 4374 series diaphragm packless oxygen purge valve</i>
46	<i>Matheson Model 4183-2505 HA3 316 SS high accuracy oxygen gas needle valve (0-3.3 slpm)</i>
47	<i>Matheson Model 8805 316 SS pressure transducer for oxygen gas (0-115 psia)</i>
48	<i>Matheson Model 8571-001 panel mountable process monitor/controller (4-20 mA output option)</i>
49	<i>Matheson 8170 Series mass flow meter calibrated for oxygen service (0-100 sccm)</i>
50	<i>Matheson 8170 Series mass flow display box calibrated for oxygen (0-100 sccm)</i>
51	<i>Newport Model Q9040BCR6-FS current display calibrated for 30 amp/50 mV Shunt</i>
52	<i>Empro 30 Amp/50 mV Shunt</i>
53	<i>Newport Model Q9040AVR3 voltage display (0-9.9999 VDC)</i>
54	<i>Newport Model Q9040TDC1 temperature display for type T thermocouple (°C)</i>
55	<i>Honeywell 7121V Series normally closed hydrogen purge solenoid valve (0-450 psig)</i>
56	<i>Honeywell 7121V Series normally closed oxygen purge solenoid valve (0-450 psig)</i>
57	<i>Momentary ON purge solenoid switch</i>
58	<i>Techlab workbench with Tecresin countertop</i>
59	<i>Swagelok bulkhead/check valve assembly for hydrogen inlet</i>
60	<i>Swagelok bulkhead/check valve assemblies for hydrogen outlet (2)</i>
61	<i>Swagelok bulkhead/check valve assembly for oxygen inlet</i>
62	<i>Swagelok bulkhead/check valve assemblies for oxygen outlet (2)</i>
63	<i>Whitey Model SS-43XS4 manual three-way hydrogen gas selection valve</i>
64	<i>Test stand electrical wire conduit</i>
65	<i>Main power switch/breaker and LED</i>
66	<i>Amp on/off load switch</i>
67	<i>Biddle adjustable carbon pile load bank</i>
68	<i>Telemecanique two pole industrial contactor (120 VAC coil)</i>
69	<i>Contactor coil 120 VAC power switch</i>
70	<i>Removed in summer of 1997: A.F. Sammer fuel cell</i>

71	Removed in summer of 1997: Cooling Fan (120 VAC)
72	Removed in summer of 1997: Product water outlet port & gas/water separator
73	<i>Swagelok</i> bulkhead connection for fuel cell hydrogen outlet
74	<i>Swagelok</i> bulkhead connection for fuel cell oxygen inlet
75	<i>Swagelok</i> bulkhead connection provision for compressed air
76	<i>Swagelok</i> bulkhead connection for fuel cell oxygen outlet
77	<i>Swagelok</i> bulkhead connection for fuel cell hydrogen inlet
78	PEM fuel cell cooling muffin fan switch/LED assembly
79	<i>Omega Engineering</i> type T dual element thermocouple
80	<i>Matheson</i> FF4374 diaphragm valve for nitrogen supply to oxygen line
81	<i>Matheson</i> FF4374 diaphragm valve for nitrogen supply to hydrogen line
82	<i>Brooks Instrument Division</i> variable area sho-rate flowmeter
83	Voltage selector switch
84	<i>Matheson</i> size 2 compressed ultra-high-purity nitrogen bottle
85	<i>Matheson</i> 401V check valve for nitrogen to oxygen line
86	<i>Matheson</i> 401V check valve for nitrogen to hydrogen line
87	Removed in summer of 2000: <i>H Power</i> fuel cell
88	<i>Ohmite</i> vitreously-enameled 100 Ω Potentiometer
89	<i>Radio Shack</i> 8 position dual-row barrier strip with 2 voltage dividers