Embry-Riddle Aeronautical University

Prescott, Arizona

College of Engineering

Hannah Spiller, Design Team Lead

Tesla Alford III

Dylan Astrup

Titan Berson

Grant Carrabine

Jacob Wolf

Abstract

The education of hydrogen production and storage is crucial to the potential future of the hydrogen economy. To accomplish the goal of hydrogen education, ERH2 proposes a hydrogen production and storage demonstrator consisting of an alkaline electrolysis system and material-based storage using Lithium-doped graphitic carbon nitride. The cost of the system will be $1154.37 and run at a maximum of 20 amps producing 0.0125 grams of hydrogen per minute. The electrolysis unit will have viewable internals to increase the educational value of the project. The design also includes a clear portable reservoir containing the material storage, allowing the storage method to be viewable to an audience. The proposed design is a safe and educational method to introduce students and the general public to hydrogen production and storage.

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Nomenclature

Abbreviation	Definition
ERH2	Embry-Riddle Hydrogen
DTL	Design Team Lead
H_2	Hydrogen Gas
ERAU	Embry-Riddle Aeronautical University
LHV	Lower Heating Value
ID	Inner Diameter
OD	Outer Diameter
DOE	Department of Energy
PTFE	PolyTetraFluoroEthylene
UHMW	Ultra High Molecular Weight Polyethylene
DC	Direct Current
STP	Standard Temperature and Pressure
TPI	Threads Per Inch
IUI	Interactive User Interface

Introduction and System Overview

Introduction

The DOE is currently funding 32 million for clean hydrogen production and storage [1]. This creates interest within Embry-Riddle to create energy lab demonstrators that teaches the engineering students about hydrogen fuel and storage.

Problem Statement

Embry-Riddle has tasked ERH2 with creating a demonstrator to produce and store hydrogen gas to run a 1-Watt fuel cell. Doing so requires the demonstrator to produce 0.002 grams of hydrogen gas every minute, store at least 0.04 grams of hydrogen gas to run the fuel cell for 20 minutes, display these values to the viewers, and maintain safety. The complete list of requirements is outlined in Appendix A: Requirements.

Purpose and Benefits

The purpose of Embry-Riddle Hydrogen is to generate and store hydrogen to power the Embry-Riddle 1-Watt fuel cell as a demonstrator to educate the population of Embry-Riddle Prescott about hydrogen as an alternative fuel source and hydrogen material storage. The design is affordable, innovative, and demonstrates the use and storage of hydrogen as a fuel. The design consists of an electrolysis machine and material storage of hydrogen gas. Electrolysis is scalable and produces more than the required 0.02 grams to run the fuel cell for 10 minutes. Material storage is an exciting new way to store the hydrogen that does not require compression and is portable. Using material storage is a great demonstrator because it is visible and safe for interaction with the public.

System Description

The ERH2 system consists of an alkaline electrolysis system that produces 0.125 grams of hydrogen every 10 minutes, graphitic carbon nitride material storage that stores at least 0.04 grams of hydrogen, and interactive displays that educate viewers on the processes. The system contains five different subsystems: the electrolysis, material storage, piping, extraction, and the interactive user interface. The ERH2 system overview is below in Figure *1*: System Configuration.

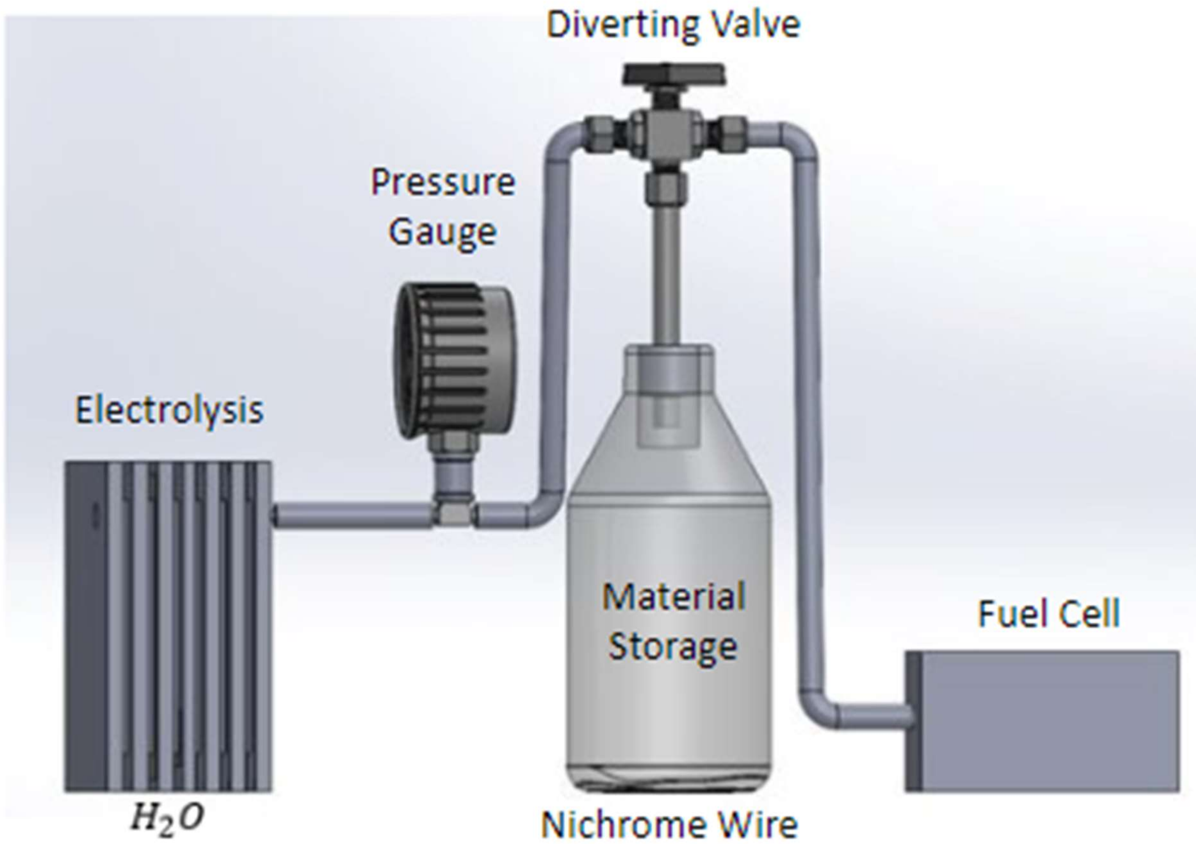

Figure 1: System Configuration

In the above figure, the electrolysis produces the hydrogen, and it flows through the piping to the diverting valve that can either directly flow to the fuel cell or flow to the material storage vessel where the material storage stores the hydrogen.

The system has three modes of operation: measurement, charging, and extraction. In the measurement mode, the diverting valve is closed to both the 1-liter graduated bottle as well as the fuel cell, creating a smaller section of the piping between the electrolysis unit and valve. This allows the pressure to build within this section of piping as the electrolysis unit runs. Measuring the pressure over a specified amount of time verifies the production rate of the electrolysis unit.

In the charging mode, the electrolysis unit is filled with saltwater solution, the diverting valve is closed to the fuel cell, and 20 amps is applied across the nickel mesh anode and cathode to produce 0.0125 grams of hydrogen per minute. The hydrogen flows from the electrolysis through ¼ inch PTFE tubing, past the connection to the pressure gauge and thermocouple, and to the 1-liter graduated bottle holding 2 grams of material storage. Once the pressure gauge reads 4 in wc on the pressure gauge, which signifies that the material storage is fully loaded with hydrogen, the power supply is shut off.

In extraction mode, the diverting valve to the electrolysis is shut, the power supply is connected to the nichrome wire, and 2.4 volts are applied. The heating of the material storage represents an exhaust flame of a rocket or the excess heat from another possible energy system. The power generated from the fuel cell is purely for demonstration purposes, otherwise the efficiency of the system is incredibly low. Once the material storage reaches 300°C, the hydrogen releases, flows up the 3 inch long ½ inch copper pipe, passes the diverting valve, flows through more PTFE tubing, to finally reach the fuel cell to power a 1 Watt LED light.

Concept of Systems Operations

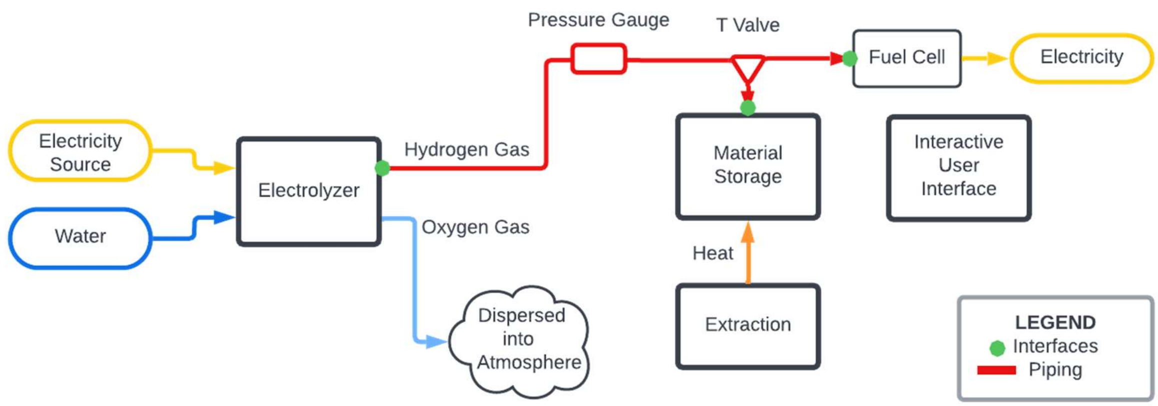

Figure 2: Process Flow Diagram

Figure 2 shows the flows through the system and how it interacts with the subsystems. The subsystems are denoted by black boxes and the legend. This illustrates the two modes of the system: electrolysis to the fuel cell or electrolysis to the material storage.

System Requirements

The ERH2 system follows five sets of system level requirements that address function, safety, education, performance, and human factors. Critical requirements are listed and described below. A full list of requirements can be found in Appendix A: Requirements.

Critical Requirements

1.1.1 The system must produce at least 0.002 grams of hydrogen gas per minute.
1.2 The system must store 0.04 grams of hydrogen gas.
2.1 The system must allow for safe extraction of hydrogen gas without risk of major leaks.
3.1 The internal system components should be visible.
4.2 The system must weigh less than 25 pounds dry.

System Governing Equations

The governing equations for the system consist of splitting water into hydrogen and oxygen gas and the amount of hydrogen the fuel cell needs to operate. Equations that directly relate to the subsystems can be found in the subsystem sections below.

$$4H^+ + 4e^- \xrightarrow{yields} 2H_2 \quad (1)$$

This equation represents the reaction of water and the cathode of an electrolysis reaction. The water reacts with electricity and yields hydrogen gas and hydroxide. This is how the electrolysis unit generates hydrogen for the system.

$$2H_2O \xrightarrow{yields} 2O_2 + 4H^+ + 4e^- \quad (2)$$

The equation above describes an anode reaction in an electrolysis of water reaction. At the anode of the circuit, water is electrolyzed and produces oxygen gas, hydrogen ions, and electrons. The amount of hydrogen required for the fuel cell can be calculated using:

$$\frac{P * t}{\eta * LHV} = m_{H_2} \quad (3)$$

Where:

P = Power Generated (kW)
t = Time Needed to Run the Fuel Cell (sec)
η = Total Efficiency of the Fuel Cell
LHV = Lower Heating Value of Hydrogen (kJ/kg)
m_{H_2} = Mass of Hydrogen Needed (g)

The amount of hydrogen required to run the fuel cell determines how much hydrogen needs to be produced and stored. This value drives the requirements for the system and subsystems.

Analysis

Using Equation 3, the amount of hydrogen needed to run the fuel cell for 10 minutes is 0.02 grams of hydrogen. This is using a desired power as 1 watt, 600 seconds for the time constant, a target fuel cell efficiency of 25%, and a lower heating value of 120,000 kJ/kg. This value was used as a metric for the critical system and subsystem requirements.

System Summary

The system can be described by the requirement fulfillment table in Appendix E. This table addresses every system requirement, the design, and the verification of the requirement.

System Verification Plans

The system verification plan is outlined in Appendix E. Table 3 describes a verification method for each requirement and a way to determine the success of each method. The core design requirements are discussed in detail below.

Requirement 1.1-1.1.1 Verification Plan

This requirement is be verified by using the pressure gauge to determine the amount of hydrogen being produced by the electrolysis unit and Faraday's Law of Electrolysis described in Equation 4. According to the calculations, the electrolysis unit produces 0.0125 grams of hydrogen every minute, exceeding the 0.002 grams per minute requirement. The pressure gauge selected has a range small enough to capture the pressure difference ___ amount of hydrogen would produce. The gauge, calculated volume, and the thermocouple give data that can then be used in the ideal gas law to calculate the mass of hydrogen in the system.

Requirement 1.2 Verification Plan
This requirement is verified by using the mass of the material storage before and after hydrogen has been introduced. When the material is sufficiently charged, the mass after should be 0.04 grams heavier. A chemistry scale, used in the ERAU labs, is needed to find the exact amount of hydrogen stored in the material.

Requirement 2.1 Verification Plan
Verification of requirement 2.1 is completed via the Bubble Test, depicted in Figure *3*.

Figure 3: Bubble test

The bubble test is a leak detection test standardized by ASHRAE. It is performed by applying soapy water to the exterior of a system then running compressed air through the interior of that system. If bubbles form in the soapy water, then there is a leak. The test can detect leaks of gas as small as ___, not as small as hydrogen, but it will give valuable information of how secure the system is on a measurable scale. ERH2 will perform the test according to the ASHRAE handbook.

Requirement 3.1 Verification Plan
To verify that the system components are visible, the system will be visually inspected to ensure that the processes are easily distinguishable to people uninvolved with the project. Willing volunteers will judge the system and describe in detail what they were able to view.

Requirement 4.1 Verification Plan

This requirement is verified by analyzing the weight of the materials in both the SOLIDWORKS part files and the manufacturers of the parts. Using these together, a total weight of the system is found to be less than 10 pounds.

Budgets

The total budget is $1300, and the system is under-budget at a cost of $1154.37. This total is broken down into the six subsystems as shown in Figure *4* below. An itemized budget can be found in Appendix C.

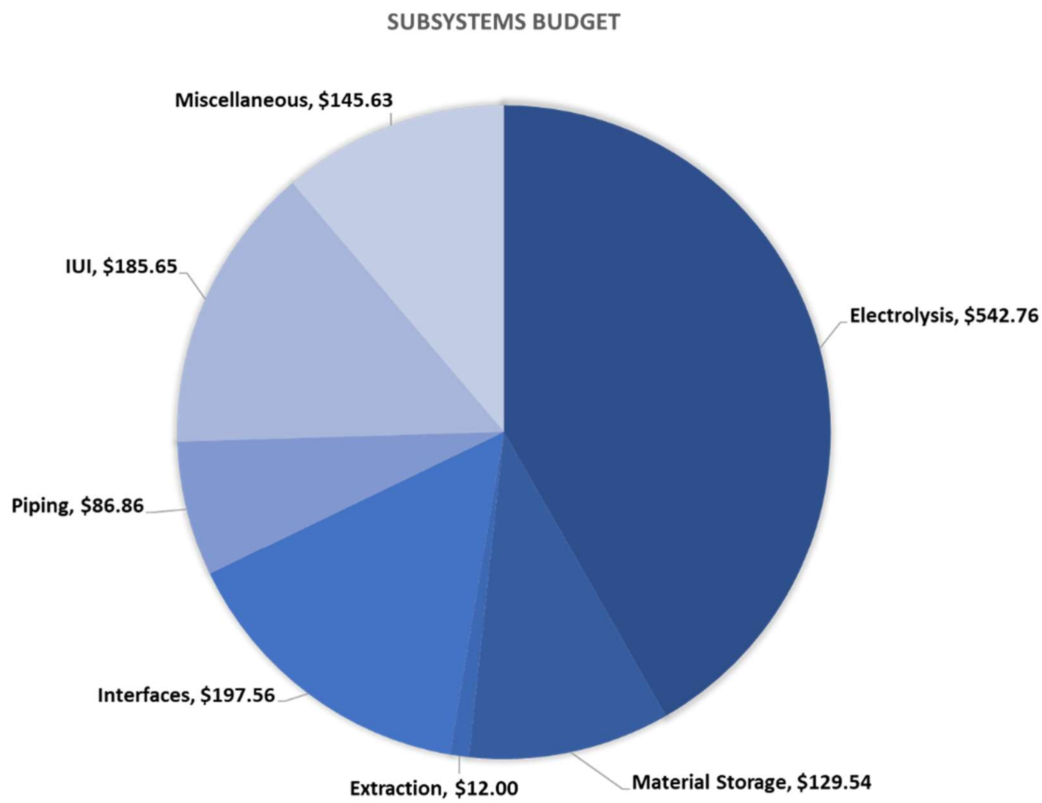

Figure 4: Subsystem Budget Chart

Electrolysis

Definition

The electrolysis system produces hydrogen by using a 6-inch x 6-inch nickel mesh with a surface area of 47.5 in^2, an electrolyte water solution, and a 20-amp power source. The nickel mesh plates are connected to the positive and negative terminals of the power source creating an anode and cathode. The cathode produces hydrogen gas, and the anode produces oxygen gas, as seen in Figure 5. The system is housed in layers of plexiglass, plastic, and sealant material which is depicted in Figure 5 below. The hydrogen flows through the piping system and the oxygen is dispersed into the atmosphere.

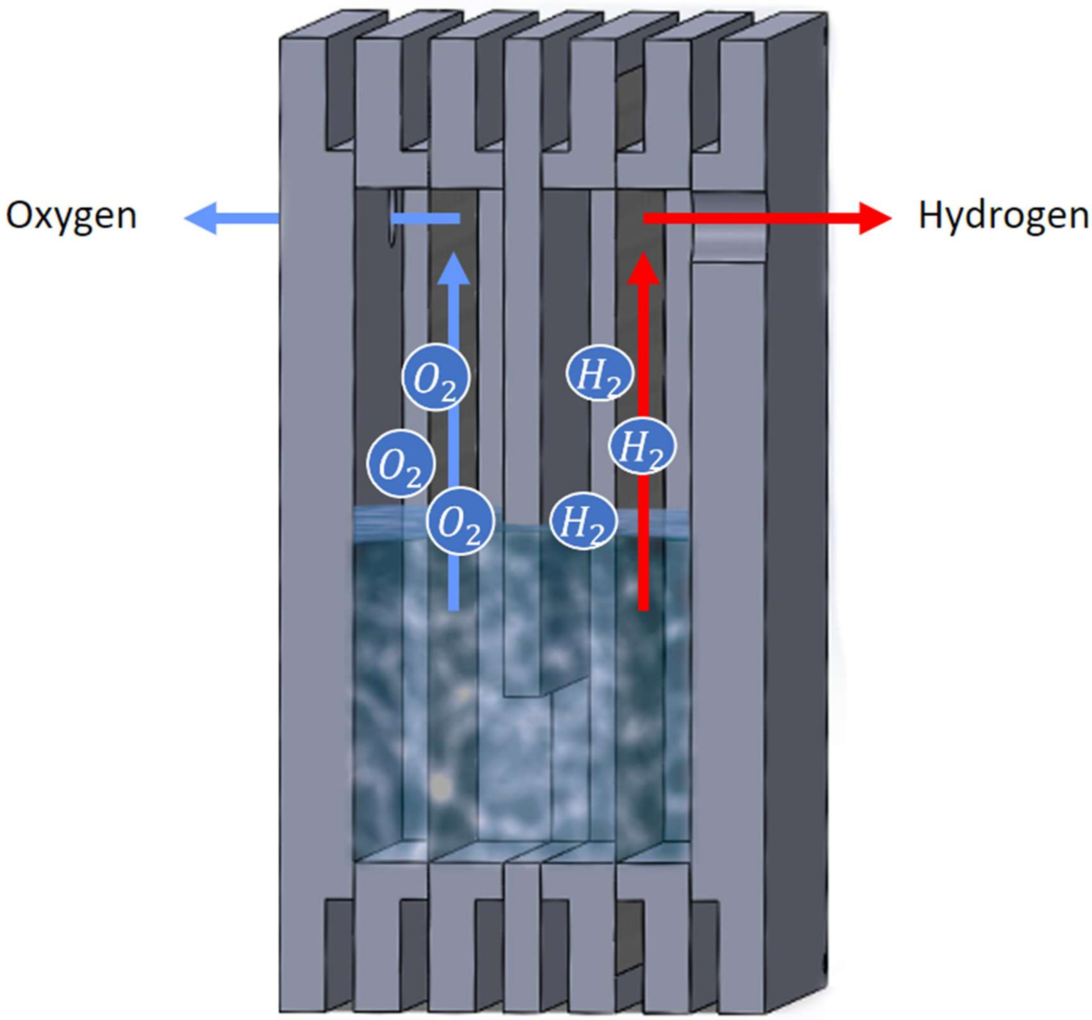

Figure 5: Electrolysis System

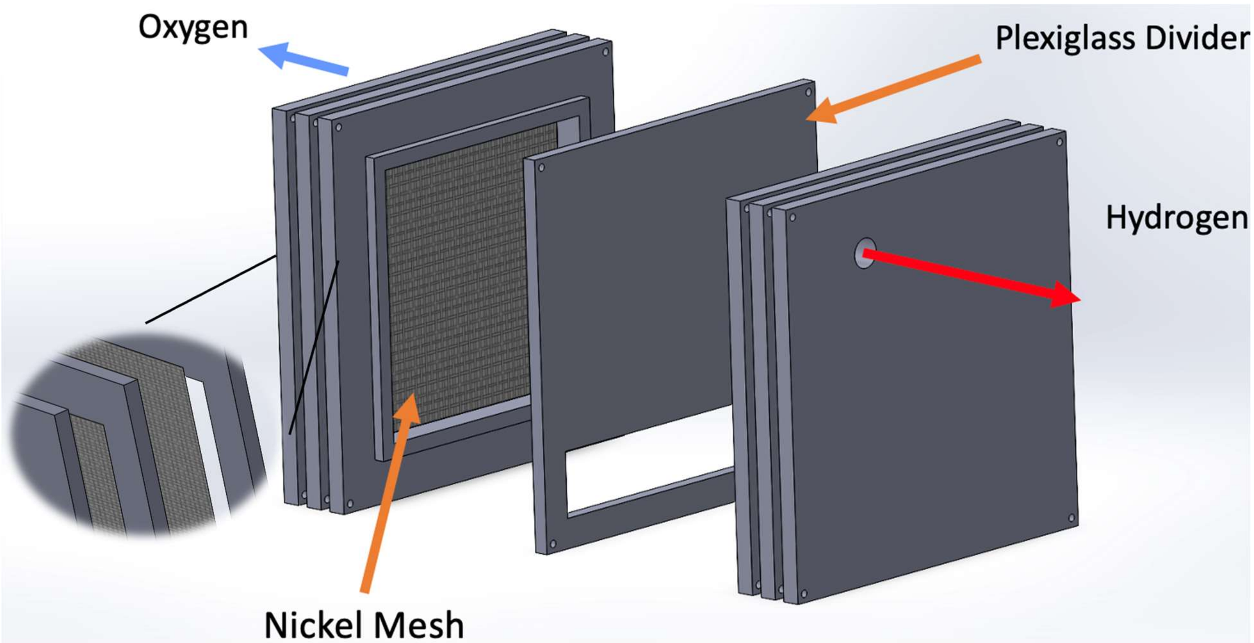

Figure 6: Exploded View of Electrolysis System

The unit consists of seven frames that are held together by four 10-32 4 inch long screws with nuts on the end to exchange layers as needed. With the mesh designed to be replaceable once there is scale build up or oxidation to the surface. The end plates are plexiglass for ease of viewing and the frames inside are made of a UHMW polyethylene plastic. Rubber tape serves as gasket material between frames in notches that seal each frame. The system is small enough to be moved by one person with a size of 6.5 x 6.5 x 3.25 in^3 and weighs 5 Lbs. The layers shown in Figure 6 hold the nickel meshes in place while the empty frames hold 49.5 in^3 of water. Wire is soldered to the outside of the nickel mesh plates and connected to the 20-amp power source.

Requirements

6.1 The hydrogen and oxygen produced in the electrolysis system must not mix.
6.2 The electrolysis system housing layers must be replaceable.
6.3 The electrolysis system housing must be resealable.
6.4 The electrolysis system housing must not be electrically conductive.
6.5 All wires must be insulated and sized according to the National Electrical Code.
6.6 The amperage applied to the electrolysis system must not exceed 20 amps.
6.7 The electrolysis system must have an emergency kill switch.

Requirements 1.1.1, 2.1, and 3.1 (Appendix A) directly address this system and call for the creation of the subsystem requirements shown above by outlining the function to create hydrogen gas, the safety of the system, and the educational benefits. 6.1 is derived from requirement 1.1.1 because the quality of the gas in the system has a direct effect on the ability to create hydrogen and effectively run the fuel cell. 6.4, 6.5, 6.6, and 6.7, are derived from requirement 2.1 to be able to safely run the system without the risk of shock, heat, and operator error. Finally, 6.2 and 6.3 are derived from 3.1 which relates the system housing to being an educational demonstrator.

Integration

The electrolysis device interfaces with plumbing through the hydrogen gas outlet and the power supply charging the nickel mesh plates. These interfaces are described in complete detail in the System Interfaces Subsystem section.

Electrical Diagram

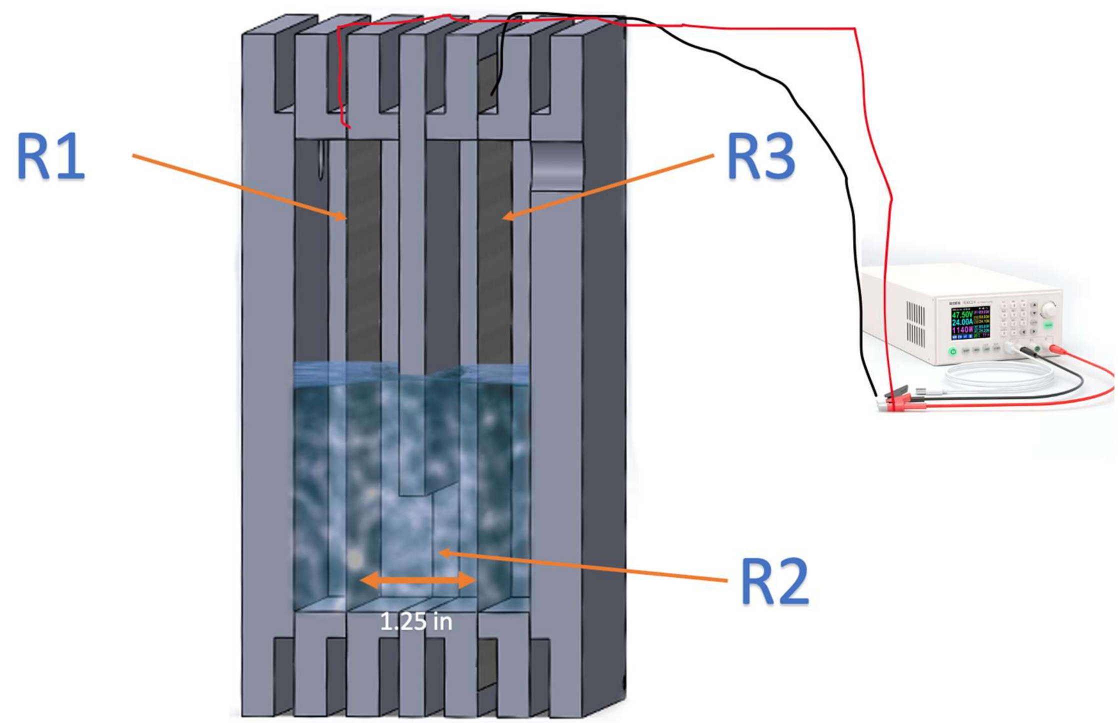

Figure 7: Visual representation of electrolysis resistors

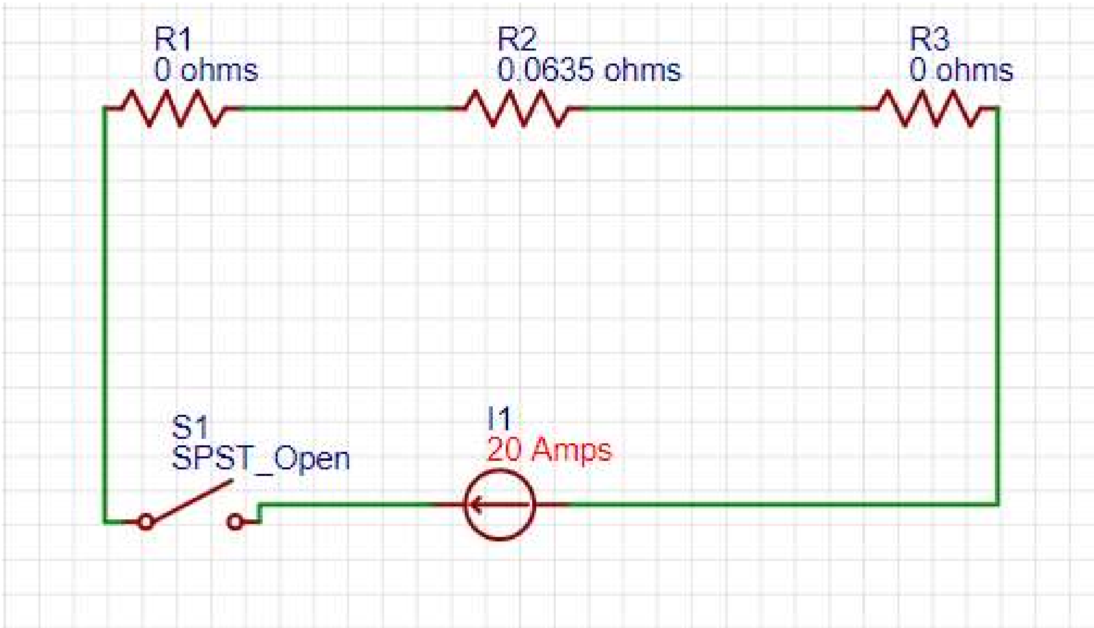

Figure 8: Circuit Diagram for Electrolysis

Figure 8 consists of a current source, a switch, and three resistors (R1, R2, and R3). The current source is supplied by the 20-amp power supply. A switch is used to turn on and off the circuit from a safe distance away from the resistors. R1 and R3 are the nickel mesh anode and cathode which have negligible resistance and R2 is the resistance from the salt water inside the electrolyzer. The channel where the salt water is stored is 1.25 inch length and the assumed resistance of the salt water can be 2 Ω/m. The calculated product from the salt water is $0.0635\ \Omega$ making the salt water the highest contributing resistance for the circuit. Using ohms law ($V = IR$) to find the voltage across the electrolyzer, the voltage across the electrolyzer circuit is less than 2 volts.

Governing Equations

Faraday's Law of Electrolysis was used to prove that the electrolysis device can meet the requirements.

$$m_{H_2 Produced} = \frac{I * M_{H_2}}{V_a} \quad (4)$$

Where:

$I\ =\ Maximum\ theoretical\ current\ (Amps)$
V_a= Valence (mol of H_2 in products/ mol of e^- in reactants)
M_{H_2}= Molar weight of hydrogen (grams/mol)
$m_{H_2 Produced}$ = Mass of hydrogen produced by electrolysis (grams)

Using this equation, the amount of hydrogen produced by the electrolysis unit can be found. This determines if the system is producing enough hydrogen to run the fuel cell and to charge the material storage quickly.

To calculate the max theoretical current first the surface area of the mesh is needed.

$$Mesh_{SA} = (2(L_{mesh} * W_{mes} \;\; + L_{mesh} * H_{mesh} + H_{mesh} * W_{mesh})) * Open\ area \tag{5}$$

Where:

$Mesh_{SA} = Mesh\ surface\ area(in^2)$
$Open\ area = Open\ area\ of\ mesh\ from\ McMaster(\%)$
$L_{mesh} = Lenght\ of\ mesh(in)$
$W_{mesh} = Width\ of\ mesh(in)$
$H_{mesh} = Height\ of\ mesh(in)$

Using this surface area, the maximum theoretical current can be calculated.

$$I = \frac{.084\ amps}{cm^2} * \frac{1\ cm^2}{.155\ in^2} * \frac{Mesh_{SA}}{1} \tag{6}$$

Where:

$I \;=\; Maximum\ theoretical\ current\ (Amps)$
$Mesh_{SA} = Mesh\ surface\ area(in^2)$

After finding the maximum theoretical current, we determined for safety of the mesh we will limit our system to 20 amps.

Analysis/Result

The electrolysis subsystem proves that it meets requirements through calculations and experimentation. Using equations 2 and 4, where applied amperage is 20 amps for safety, 10 minutes (600 seconds), 2.007 grams for molar weight of hydrogen, and Faraday's constant 96,485 C/mol. The amount of hydrogen the electrolysis generates in 10 minutes is 0.125 grams. The finished calculation is shown below.

$$m_{H_2} = \frac{20\ (C)}{1\ (s)} * \frac{600\ (s)}{96{,}485\ (C)} * \frac{2\ (mol\ H_2)}{4\ (mol\ e^-)} * \frac{2.007\ (g\ H_2)}{1\ (mol\ H_2)} = 0.125g\ of\ H_2\ per\ 10\ minutes$$

Subsystem Verification Plans

To verify that the electrolysis device is meeting requirements, it must follow the experimentation verification plans described below.

Requirement 6.1

The hydrogen and oxygen gases within the system do not mix due to the dividing layer's channel. To verify the sides do not mix, composition tests will be run to ensure that only hydrogen is coming out of the hydrogen outlet.

Requirements 6.2-6.7

These requirements are met and verified through simple checks in the system. The system verification matrix in Appendix E outlines the checks in detail.

Subsystem Summary

The electrolyzer produces hydrogen at the rate of 0.125 grams per 10 minutes using a 20-amp DC power source. The oxygen byproduct and is released into a ventilated area, while the hydrogen flows through the system. The electrolyzer also serves as a demonstrator by showing the internals of the device.

Storage

Definition

The material storage, lithium-doped graphitic carbon nitride, absorbs the hydrogen gas produced by electrolysis and then releases it to the Embry-Riddle fuel cell. This material storage is an exciting new way to store hydrogen because it is lighter than conventional methods. Compressed hydrogen tanks can hold __% of its weight in hydrogen while lithium-doped graphitic carbon nitride can hold up to 10%. A maximum of 20 grams of material is placed in a graduated bottle made of chemistry glass and hydrogen flows in, as seen in Figure 8. Fully charged, the material holds 0.04 grams of hydrogen that can be stored indefinitely STP. To release the hydrogen, the material is heated to 300°C using the nichrome wire to loosen the bonds holding the hydrogen and release the stored hydrogen to run the fuel cell.

To manufacture the material, urea is placed in a kiln and

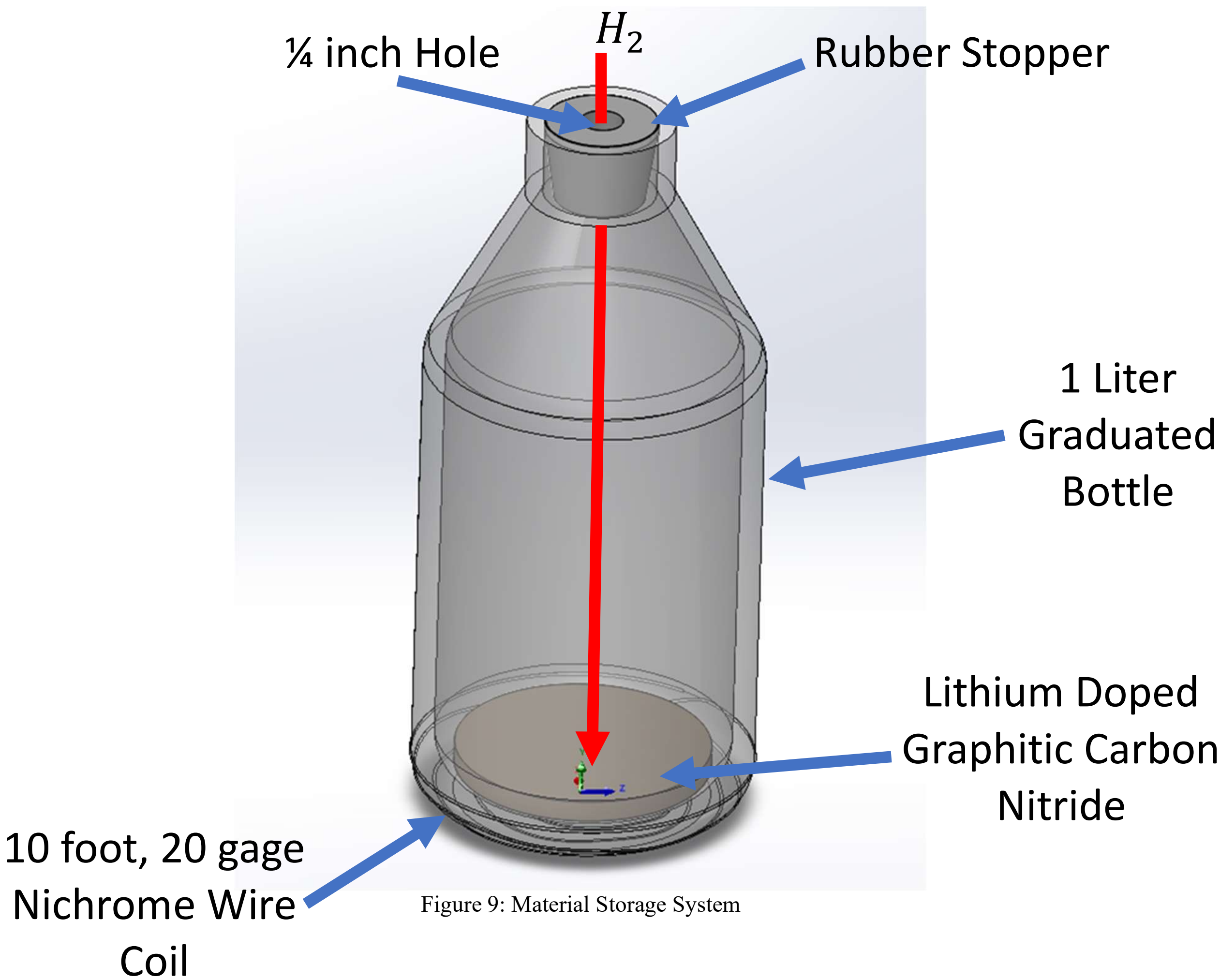

Figure 9: Material Storage System

Requirements

7.1 Material storage must release hydrogen at 0.02 grams every 10 minutes.
7.2 Material must store hydrogen with at least 2% weight of Hydrogen.

7.3 Must contain at least 20 grams of material storage.

The material storage has two system requirements; it must store 0.04 grams of hydrogen (1.2) and must be at least 50% efficient (hydrogen in vs. hydrogen out) (4.1). The three subsystem requirements support these requirements by storage capacity and amount of material needed. Requirement 7.1 describes the rate the material must release hydrogen to consistently run the fuel cell derived from 1.1.1 which requires that the fuel cell must run for 10 minutes. Requirement 7.2 specifies the hydrogen storing properties of the material derived from 1.2 that states that the material must hold at least 0.04 grams of hydrogen. Finally, Requirement 7.3 outlines the quantity of material needed to be produced from 1.2 to meet the storage goals.

Integration

The material storage integrates with the interface and extraction subsystems. The graduated bottle for the material storage is connected to the rubber stopper of the interfaces system and the nichrome wire of the extraction system. The extraction system heats the material to 300°C to release the stored hydrogen. The rubber stopper of the integration subsystem seals the bottle and connects the hydrogen to the copper pipe. Further explanation of interfaces is in the Interfaces section.

Governing Equations

To prove the material storage can meet the requirements, simple calculations on the weight of the material and efficiency equations were used.

$$\eta_{Material} = \frac{m_{H_2out} - m_{H_2in}}{m_{H_2in}} \tag{7}$$

Where:

$\eta_{Material}$ = Material efficiency
m_{H_2in} = Mass of hydrogen into the material storage system
m_{H_2out} = Mass of hydrogen leaving the material storage subsystem

Equation 5 calculates the efficiency of the material based on the amount of hydrogen it needs to charge and the hydrogen the material releases. This indicates how effective the material is at absorbing the hydrogen that is entering the vessel and releasing the hydrogen.

$$m_{Sto} \quad = m_{final} - m_{initial} \tag{8}$$

Where:

m_{Stored} = Mass of hydrogen stored in material storage
$m_{initial}$ = Mass of the storage before hydrogen is introduced
m_{final} = Final mass of the material after hydrogen loading

The mass of the hydrogen that the material can hold is important because it indicates the completion of requirement 1.2. The mass of the stored hydrogen is found using equation 6.

$$\%_{wtH_2} = \frac{m_{Stored}}{m_{final}} * 100 \tag{9}$$

Where:

$\%_{wtH_2}$ = Weight percentage of hydrogen in the material storage

To fulfill requirement 7.2, the weight percentage of hydrogen in the material must be at least 2%. Equation 7 will find this by using the stored mass of hydrogen to the final mass of the material.

Analysis/Result

Graphitic carbon nitride exceeds all the subsystem requirements verified by experimentation and research. There is currently no information on the release rate of the material, but it is scalable and controllable at the diverting valve to account for slow release. According to a study on lithium-doped graphitic carbon nitride for hydrogen storage, the maximum hydrogen storage capacity of the material is 10% wt hydrogen [1]. This exceeds requirement 7.2 and gives space for development and experimentation to fulfill the 2% goal. To manufacture 20 grams of material as stated in 7.3, 5000 grams of synthesis material is needed. The materials urea and lithium chloride are easily accessible and affordable.

Subsystem Verification Plans

To verify that the material storage is meeting requirements, it must follow the storage verification plans specified below.

Requirement 7.1 Verification Plan

To verify that the material storage will meet this requirement, the material will be heated by the extraction subsystem and the released hydrogen will flow to the fuel cell. If the fuel cell powers the 1-Watt LED light, then the material storage fulfills the requirement. The tools needed for this test are the fuel cell, the extraction system as a heat source, the 1-Watt LED light, a stopwatch to measure the time, hydrogen gas, and the piping and interfaces to direct flow. The test will be conducted in a well-ventilated area on the Embry-Riddle Prescott campus. To record the results of the test, an excel document will record the time the light was on to determine how long the storage can run the fuel cell. To safely perform the test, the experiment area will be ventilated, and heat protectant gear will be worn by operators.

Requirement 7.2 Verification Plan

If the storage capacity of the material storage is at the minimum of 2% wt hydrogen, the maximum amount of storage needed to hold 0.04 grams (requirement 1.2) is 2 grams. The material is put in a sealed container, measured, and hydrogen is added. To verify that the material storage is meeting this requirement, tests are conducted to measure the stored hydrogen in the material and then using equation 9. The necessary tools needed for this experiment is a sealable container, the material to be tested, a scale to measure the mass of the material, and hydrogen gas. The test is performed on the Embry-Riddle Prescott campus like a vent hood, found in STEM building room 122, or in an open area that is ventilated. To track the results the weight percentage of hydrogen is recorded and compared to 2% to verify the requirement.

Requirement 7.3 Verification Plan

This gives a guide on how much of each ingredient needs to be purchased to store at least 0.04 grams of hydrogen. This is verified by synthesizing the material and weighing it to verify that it is at least 20 grams. The tools necessary for the experiment are a scientific scale, urea, and lithium chloride. This test is performed in the materials lab and the results are recorded in the final report.

Subsystem Summary

The material storage, graphitic carbon nitride, must store 0.04 grams of the available hydrogen produced and release it with an efficiency of 50%. Based on these requirements, the material must also release the hydrogen, have a capacity of 2% wt hydrogen, and make at least 20 grams. According to research and analysis, the lithium doped graphitic carbon nitride meets these requirements. The subsystem requirement verification table can be found in Appendix E.

System Integration

Definition

System Integration reviews the steps that ERH2 will use when designing, building, and testing each connection where two or more subsystems meet. Subsystem requirements 8.1, 8.2, and 8.3 enforce ERH2's design for the electrolysis, the pressure gauge, and the material storage respectively. There will be several fittings that consist of the following: The barbed fitting, the 3 way barbed insert, the 3 way diverting valve, and the rubber stopper. Each primary interface has its own detailed sections continued in the System Integration.

Requirements

8.1 All interfaces at the electrolyzer will be properly accounted for and sized.
8.2 All interfaces at the pressure gauge interface will be properly accounted for and sized.
8.3 All interfaces at the material storage interface will be properly accounted for and sized.

Integration

Throughout the system, several primary interfacers are installed to ensure leak-proof connections. The term Primary Interface is given to any componet or componets that connect two or more subsystems. A system map, Figure 9, has been created to aid with locating each primary interface.

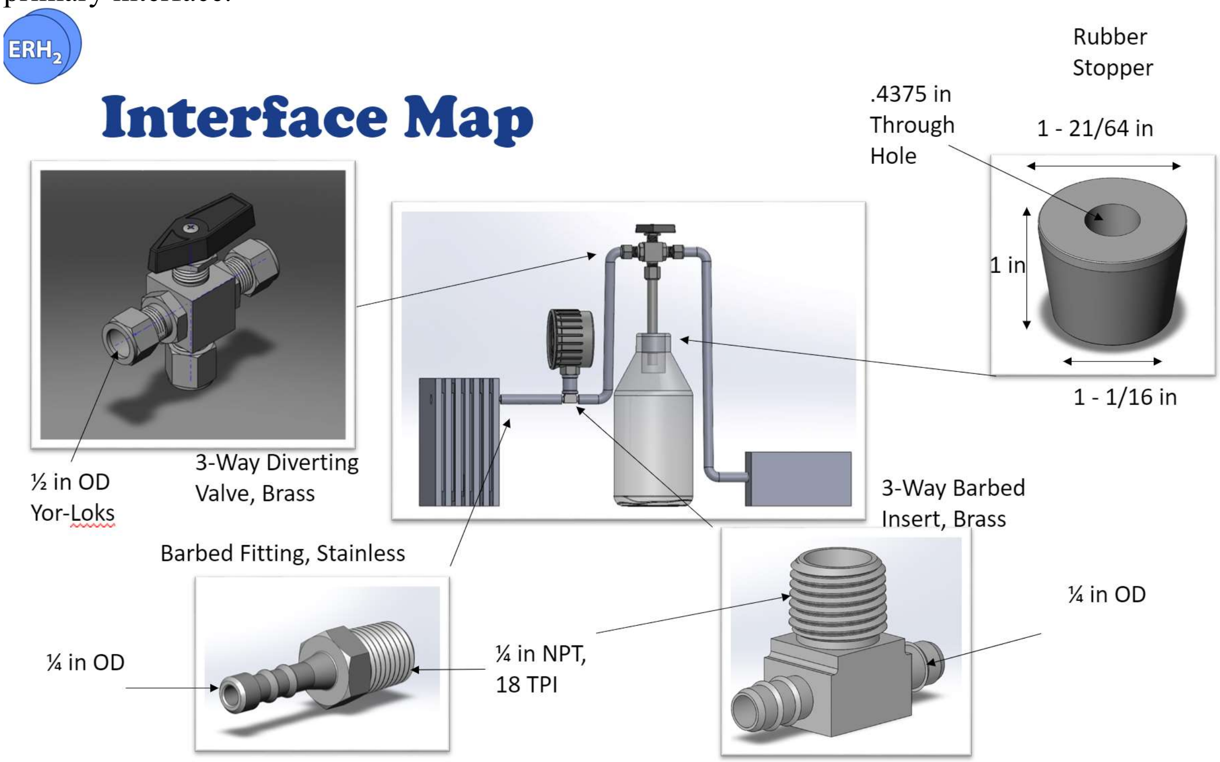

Figure 10: Primary Interface Map

Along with a magnified image of the primary interface, more information has also been attached such as the material type and major dimensions. A further induvial analysis will be conducted on each primary interface.

Barbed Fitting

The barbed fitting connects the electrolyzer to the piping subsystem. The casing for the electrolyzer is Plexiglass and the piping is ¼ ID PTFE piping. To achieve an airtight connection, A stainless-steel barbed fitting is used. The electrolyzer fitting is a ¼ in, 18 TPI male threaded adaptor with a ¼ inch ID male barbed fitting. The barbed insert can slip onto the PTFE piping and form an airtight seal. Figure 11 the barbed insert.

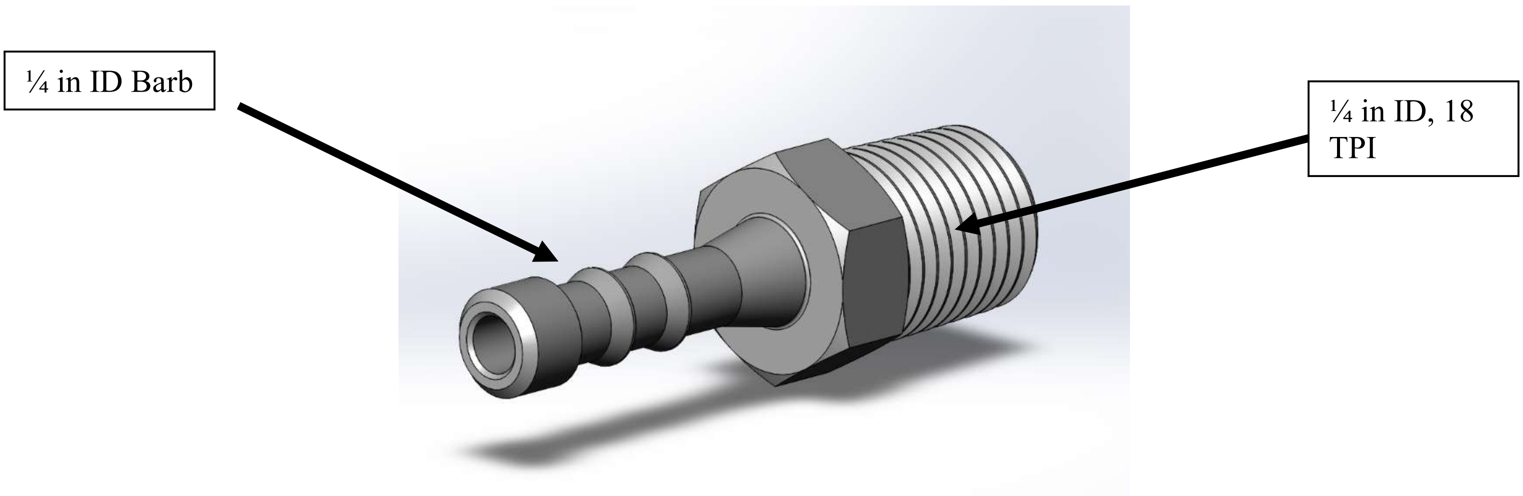

Figure 11: Barbed Fitting

3 Way Barbed Insert

The 3 Way Insert is like the Barbed Fitting in Figure 11. Both barbed inserts are ¼ ID and the male threaded connection is ¼ inch ID, 18 TPI. The fitting is made of brass to avoid hydrogen embrittlement. This insert allows for a pressure gauge to be attached to a female-to-female fitting, where the pressure gauge is screwed into place. Figure 12 shows the 3 Way Barbed Insert.

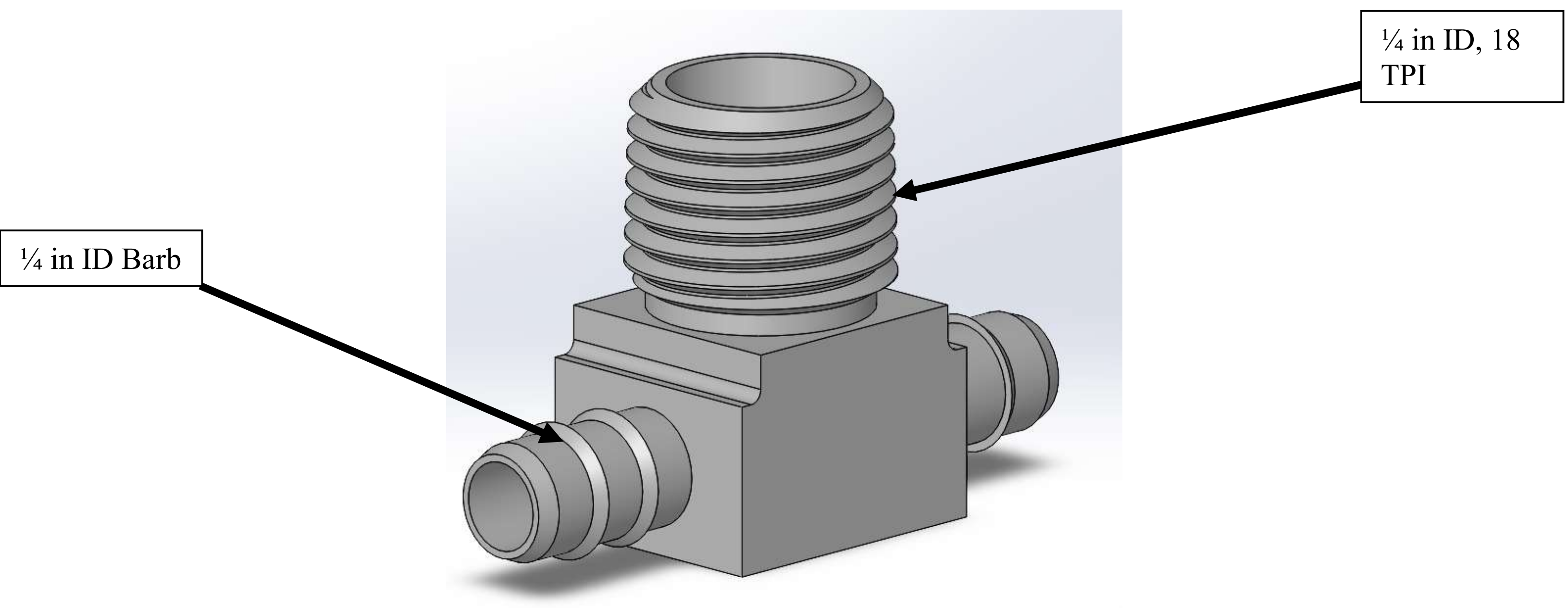

Figure 12: 3 Way Barbed Insert

3 Way Diverting Valve

The 3 Way Diverting Valve connects the copper piping between the material storage and the PTFE tubing from the pressure gauge, and from the fuel cell. The diverting valve controls the flow of hydrogen from the position that the handle faces. The diverting valve is made specifically for hydrogen gas, as the locking mechanisms are ½ in OD Yor-Lok's. A Yor-Lok allows a pipe of a fixed diameter to be slotted inside of its hexagonal nuts. After the pipes have been inserted, the nut is turned to lock the pipe into place. From this locking process, the interface is airtight. The diverting valve is also made from brass to prevent hydrogen embrittlement. The PTFE and the copper pipe connect to the Yor-Lok's. To release pressure build-ups, segments of the piping system can be removed while keeping the rest of the system secure. Figure 13 shows the 3 Way diverting valve.

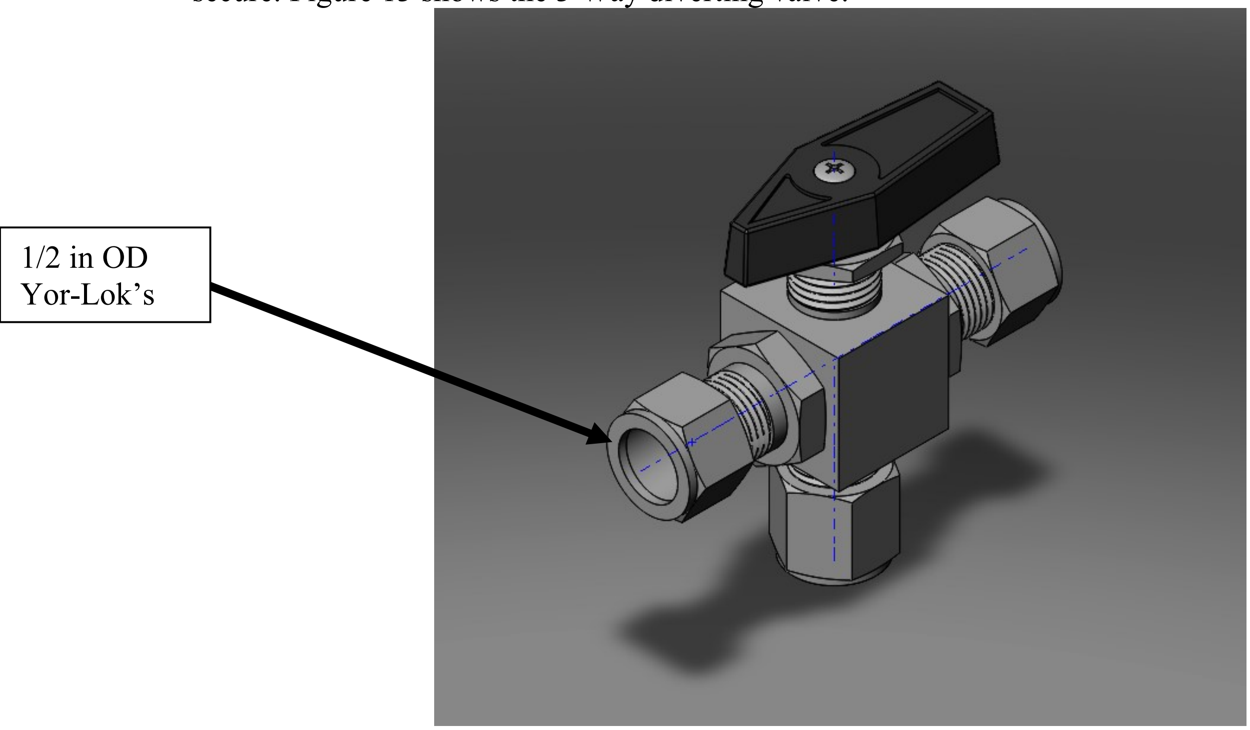

Figure 13: 3 Way Diverting Valve

Rubber Stopper

The rubber stopper is the final primary interface. For more specific dimensions review Figure 10. The rubber stopper acts as a non-intrusive and removable interface for the graduated bottle that holds the material storage. Figure 14 is the rubber fitting.

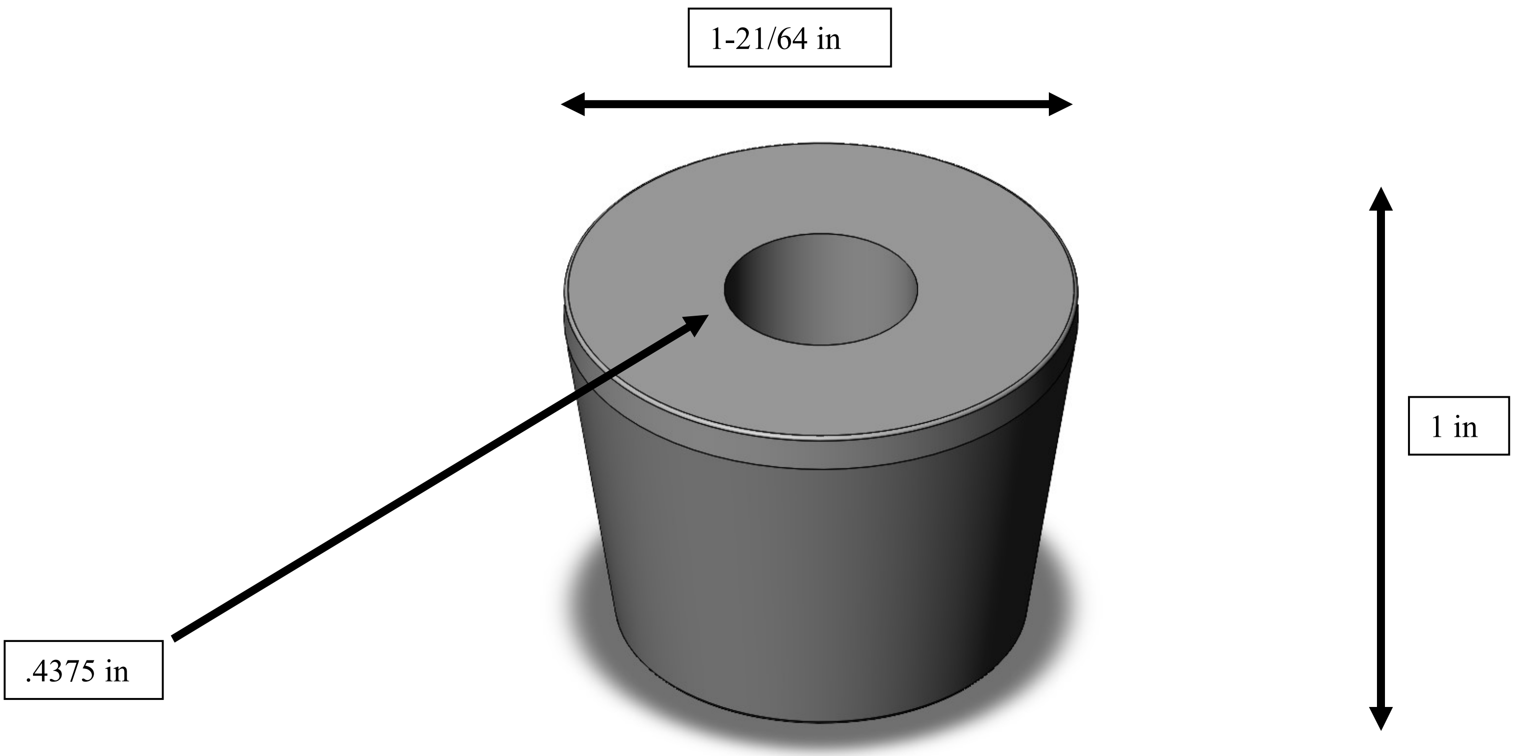

Figure 14: Rubber Stopper Fitting

Other Connections

Other interfacing areas require a bonding agent to prevent leaks. For these interfacing areas, a series of epoxies secure an airtight connection. Table 1 gives data on these regions that require epoxies. If the epoxies fail bubble test, a threaded connection will be considered. These interfaces are not primary interfaces since they do not directly connect two or more subsystems together.

Table 1: Specific Interfacing Connections

Type of Interface	Name	Price	Interface Point
Plastic Epoxy	Plastic Epoxy Putty	$5.83 per 2 ounces	Electrolyzer to piping connection
Electrical Epoxy	Fire Barrier Sealant	$11.28 per 10.3 ounces	Electrical Epoxy for Electrolyzer
Gasket Tape	NEMA 12	$15.55 per 10 feet	Internal Electrolyzer Interfaces
Pipe Gasket	Gasket	$0.79 each	Threaded Connections
Plastic Epoxy	J-B Weld	$9.76 per 2 ounces	Electrolyzer Water Storage Casing
Threaded Connections	Made Inhouse	1/2 inch Aluminum Stock	To be Decided

Subsystem Verification Plans

To verify that all connections are airtight, the bubble tests is used to test seals. Soapy water is applied on all interfaces and air is pushed through the system. If any bubbles occur at the interfaces, then a leak has been found. If a leak is found, a change in gasket, sealant, or interfacing component will be made. Once the change has been implemented, the test is repeated.

Subsystem Summary

All interfacing regions both major and minor has an airtight connection and is tested using the bubble test. If an interfacing area fails, then a new design will be considered and tested to guarantee that no leaks occur on the final design. The verification plans can be found in Appendix E.

Extraction

Definition

The extraction system allows for hydrogen gas to be safely pulled from the material storage medium, graphitic carbon nitride, for transportation and use by the fuel cell or other demonstration methods. This is achieved by heating the storage medium to a temperature of 300°C to cause hydrogen release. A 10ft length of nichrome wire is used as a resistance heater to meet this target temperature. The wire is coiled beneath the graduated container, which holds the storage medium, and above an insulating layer of aerogel. A voltage is applied through use of a power supply unit to control wire temperature.

Requirements

9.1 The heating system must be able to cause the material storage to release hydrogen….
9.2 The heating system must be able to heat the storage material to 300°C and must not exceed 350°C.

Extraction requirement 9.1 is derived from system requirement 4.3, the material storage to fuel cell system must be able to run for 10 minutes. Requirement 9.1 sets an upper bound on the heat rate applied to the storage material through enforcing a pressure limit. This pressure limit is from the manufacturer's specifications for our fuel cell and exceeding this limit would damage the fuel cell, preventing it from running at all and therefore failing system requirement 4.3. Extraction requirement 9.2 is derived from system requirement 2.1. This requirement sets an upper bound on the temperature of the heating elements to mitigate the risk of melting temperature sensitive components made from plastics within the piping system. Melting these components would cause hydrogen gas leaks and fail system requirement 2.1.

Integration
This system is integrated into the storage system as a 10ft. coil of Nichrome wire placed beneath the graduated bottle to serve a s a resistance heater. Power leads are run from either end of the Nichrome coil to a power supply unit to provide the necessary voltage to meet subsystem requirements.

- Type: Resistance Wire
- Material: Nichrome 80 Alloy (nom. 80% Ni, 20% Cr)
- Color: Silver
- Specification: ASTM B267
- Temperature Rating: 1177°C (2150°F)
- Spool Sizes Available: 25 ft, 100 ft, 250 ft, 500 ft, 1000 ft, 2500 ft, 5000 ft

20N80	20 AWG	0.0320"	

Figure 15:Nichrome Wire Specifications *[2]*

Governing Equations
This system is governed by heat transfer, to determine required power input for our target steady state temperature of 300°C, and electric power to determine voltage input for our desired power given the heating element.

$$Heat\ Rate\ Out = Conduction\ loss + Convection\ loss \quad (10)$$

$$\text{Convection } loss = h_{air} A_1\, \Delta T \quad (11)$$

$$\text{Conduction } loss = -k A_2 \Delta T \quad (12)$$

Where:

$h_{air} = 2.5$ for still air

$A_1 = .0038m^2$ (50% surface area of heating element)

$A_2 = .0019m^2$ (25% surface area of heating element)

$k = 11.3 \frac{W}{m * °K}$

$\Delta T = 280°$

Equation 8 calculates the heat rate of losses to the surroundings at our target temperature of 300°C. This is a summation of Equations 9 and 10 which account for the main sources of heat loss. The resistance of our heating element, nichrome wire, increases with temperature. Testing by Brysonics found that electrical resistance increased by 7% when heating from 20°C-400°C [3].

$$Q = V^2/R \quad (13)$$

Where:

Q = Heat rate out

$R = .705 \frac{\Omega}{m} * 3.048m$

Equation 11 calculates the required voltage input given the resistance of our heating element and the expected losses at the target temperature calculated as heat rate out by equation 8.

Analysis/Result
Through mathematical analysis we obtain the following values:
- Convection Loss: 2.6812W
- Conduction Loss: 0.0014W

- Heat Rate Out: 2.683W
- V(Voltage): 2.402V

Constants utilized in the calculations of these values are sourced from manufacturer's data sheets and articles related to convection to free convection air. This is inferred from our design which does not allow for rapid airflow due to convection of heated air. [2]–[4]

Subsystem Verification Plans

This subsystem is verified through experimentation for hydrogen flow and thermal imaging for confirmation of temperatures. The extraction system is ran with gradually increasing power provided to the resistance heating element. At each power graduation a thermal image is captured to verify the steady state temperature given the current input. Once the target temperature has been reached, the piping system is connected to the fuel cell allowing hydrogen to flow.

Subsystem Summary

The extraction subsystem heats the material storage to a target temperature of 300°C, releasing the stored hydrogen for use by the fuel cell or other demonstration methods.

Piping

Definition

The piping moves hydrogen gas between the electrolyzer, material storage, and fuel cell, as shown in Figure 16.

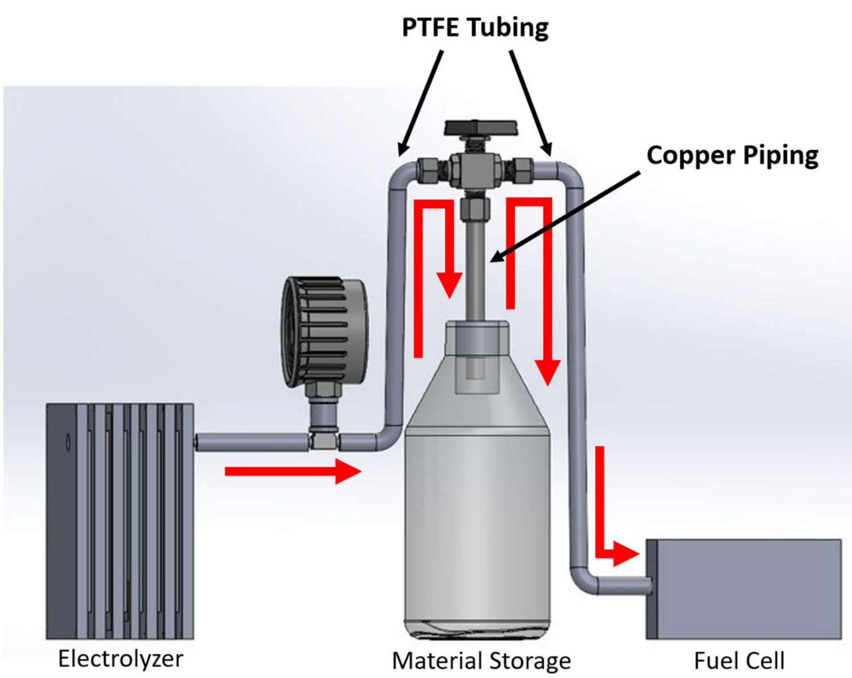

Figure 16: Piping Layout

The PTFE tubing connects the electrolyzer and fuel cell to the diverting valve, and the copper pipe connects the diverting valve to the material storage. This enables the flow of hydrogen gas through the system.

Requirements

10.1 The subsystem must transport hydrogen gas from the electrolyzer to the material storage, and from the material storage to the fuel cell.
10.2 The subsystem must withstand internal pressures up to 40.43psi absolute without leaking.
10.3 The subsystem must withstand temperatures up to 350°C without leaking.

Requirement 10.1 was decomposed from requirement 4.3. Running the fuel cell using the material storage necessitates a method of transporting hydrogen gas between electrolyzer, material storage, and fuel cell.

Requirements 10.2 and 10.3 were decomposed from requirement 2.1. In order to prevent risk of leaks, the piping system must withstand internal pressures up to 40.43psia and temperatures up to 350°C, which are the highest pressure and temperature that could be created during the extraction process.

Governing Equations

Reynolds Number for Flow in a Circular Tube [5, p. 476]:

$$Re = \frac{4\dot{m}}{\mu \pi D} \tag{14}$$

Where:

$\dot{m}$ = mass flow rate (kg/s),
μ = dynamic viscosity (kg/m*s),
D = inner diameter of the tube (m).

Rate of Heat Transfer from a Fin with a Specified Fin Tip Temperature [5, p. 175]:

$$\dot{Q} = \sqrt{hpkA_c}(T_b - T_\infty)\frac{cosh(mL) - [(T_L - T_\infty)/(T_b - T_\infty)]}{\sinh{(mL)}} \tag{15}$$

Where:

$m = \sqrt{hp/kA_c}$,
h = convective heat transfer coefficient between fin and bulk air (W/m^2*K),
p = perimeter of the fin (m),
k = thermal conductivity of the fin (W/m*K),
A_c = cross-sectional area of the fin (m^2),
T_b = temperature at the fin's base (°C),
T_∞ = temperature of the bulk air (°C),
T_L = temperature at the fin's tip (°C),
L = length of the fin (m).

External Convective Heat Transfer Coefficient for a Vertical Cylinder [5, p. 382] :

$$h = \frac{Nu_L k}{L} \tag{16}$$

Where:

Nu_L = Nusselt number,
k = thermal conductivity of the bulk air (W/m*K),
L = length of the cylinder (m).

Nusselt Number for a Cylinder [6]:

$$Nu_L = Nu_{L,fp}\left(1 + 0.3\left[32^{0.5} Gr_L^{-0.25}\frac{L}{D}\right]^{0.909}\right) \tag{17}$$

Where:

$Nu_{l,fp}$ = Nusselt number for a flat plate,
Gr_L = Grashof number,
L = length of the cylinder (m),
D = outer diameter of the cylinder (m).

Nusselt Number for a Flat Plate [6]:

$$Nu_{L,fp} = 0.68 + \frac{0.670 Ra_L^{\frac{1}{4}}}{\left[1 + (0.492/Pr)^{\frac{9}{16}}\right]^{\frac{4}{9}}} \tag{18}$$

Where:

Ra_L = Rayleigh Number,
Pr = Prandtl Number.

Grashof Number [5, p. 539]:

$$Gr_L = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2} \tag{19}$$

Where:

g = gravitational acceleration (m/s^2),
β = coefficient of volume expansion (1/K),
T_s = temperature of the surface (°C),
T_∞ = temperature of the bulk air (°C),
L_c = length of the cylinder (m),

ν = kinematic viscosity of the fluid (m^2/s).

Rayleigh Number [5, p. 541]:

$$Ra_L = Gr_L \, \mathrm{Pr} \tag{20}$$

Where:

Gr_L = Grashof Number,
Pr = Prandtl Number.

Curvature Parameter [6]:

$$\xi = \frac{4L}{D}\left(\frac{Gr_L}{4}\right)^{-\frac{1}{4}} \tag{21}$$

Where:

L = length of the cylinder (m),
D = outer diameter of the cylinder (m),
Gr_L = Grashof Number.

Analysis/Result

To prevent thermal cycling in the system, and consequently satisfy requirement 10.3, the pipe leaving the material storage must convect away enough heat during the extraction process so the hydrogen gas is 50°C or less when it reaches the diverting valve. Copper was chosen due to its high thermal conductivity, and pipe with an outer diameter of 0.5 inches and an internal diameter of 0.45 inches was chosen due to its inexpensiveness [7]. A length of 3 inches was chosen to match the scale of relative scale of the rest of the system. The following heat transfer analysis shows that these dimensions are sufficient to reduce the hydrogen gas temperature from 350°C to 50°C, with a factor of safety of 15.

Design Principals:

- Fluid properties in internal flow must be evaluated at the bulk mean fluid temperature to account for changes over the range of temperatures. This value is the average of the inlet and outlet temperatures [5, p. 482]. A fluid cooling from 350°C to 50°C has a bulk mean fluid temperature is 200°C.
- Fluid properties in external flow must be evaluated at the film temperature to account for changes over the range of temperatures. This value is the average of the surface temperate and the surrounding air temperature [5, p.405]. The surrounding air temperature used in this analysis is 20°C, so when the surface is at 350°C the film temperature is 185°C.
- Fluid properties are found using the tables in [5, p. 926 & 927]. [8] and [9] are used to find other necessary properties. Linear interpolation is used when necessary.

This situation cannot be treated as a fluid flow problem due to small mass flow rate and Reynolds number:

To operate at 1 watt for 10 minutes, the fuel cell needs 0.02 grams of hydrogen gas. This results in a mass flow rate of

$$\dot{m} = \frac{0.02(g)}{10(min)} \frac{1(min)}{60(s)} \frac{1(kg)}{1{,}000(g)} = 3.33 * 10^{-8}(kg/s).$$

The Reynolds number of this flow regime (where hydrogen gas is at the bulk mean fluid temperature of 200°C) is

$$Re = \frac{4 * 3.3E^{-8}(kg/s)}{1.23E^{-5}(kg/m * s) * \pi * 0.01143(m)} = 0.302.$$

This number is small: for context, Reynolds numbers of internal flow are generally four orders of magnitude larger, and Re = 2,300 is the lower limit for internal laminar flow [5, p. 476]. The small mass flow rate and Reynolds number indicate that bulk fluid motion does not accurately describe the movement of energy and mass within the system, so this cannot be treated as a fluid flow problem.

Because this situation isn't a fluid flow problem, it is more accurately described as a power balance on the extraction process. As detailed in the Extraction subsystem above, the nichrome wire introduces 2.683 watts of power during extraction. The copper pipe must be shown to remove this amount of power under the worst-case scenario:

- Only the copper pipe moves energy out of the system.
- This energy is moved only via natural convection between the copper pipe and bulk air.
- The copper pipe starts at 350°C and cools to 50°C.

In this worst-case scenario, the copper pipe can be treated as a finned surface with a specified fin tip temperature, as described by equation 15. Equation 15 requires the convective heat transfer coefficient, found using equation 16. Equation 16 requires the Nusselt number.

The Nusselt number cannot be found by treating the cylinder like a vertical plate, which would be allowed if $D \geq 35L/Gr_L^{1/4}$ [5, p. 543]. This is because, at the film temperature 185°C,

$$Gr_L = \frac{9.81(m/s^2) * 0.00217(K^{-1}) * \left(350(°C) - 20(°C)\right) * 0.0762^3(m^3)}{(3.27 * 10^{-5})^2(m^2/s)^2} = 2.90 * 10^7,$$

$$\frac{35L}{Gr_L^{1/4}} = \frac{35 * 0.0762(m)}{(2.90 * 10^7)^{1/4}} = 0.0646(m),$$

and

$$D = 0.5(in) = 0.0127(m) \not\geq 0.0646(m).$$

At this temperature,

$$Pr = 0.699$$

and

$$\xi = \frac{4 * 0.0762(m)}{0.0127(m)} \left(\frac{2.90 * 10^7}{4}\right)^{-\frac{1}{4}} = 0.822.$$

Because $0.01 \leq Pr \leq 100$ and $0 < \xi < 5$, the Nusselt number can be found using equation 17 [6]. This results in

$$Ra_L = (2.90 * 10^7) * (0.699) = 2.03 * 10^7,$$

$$Nu_{L,fp} = 0.68 + \frac{0.67 * (2.03 * 10^7)^{1/4}}{\left[1 + (0.492/0.699)^{\frac{9}{16}}\right]^{\frac{4}{9}}} = 20.0,$$

$$Nu_L = 20.0\left(1 + 0.3\left[32^{0.5} * (2.90 * 10^7)^{-0.25} \frac{0.0762(m)}{0.0127(m)}\right]^{0.909}\right) = 24.5,$$

$$h = \frac{24.5 * 0.0367(W/m * K)}{0.0762(m)} = 11.8(W/m^2 * K),$$

$$p = D_{out}\pi = 0.0127(m) * \pi = 0.0399(m),$$

$$A_c = \frac{1}{4}\pi(D_{out}^2 - D_{in}^2) = \frac{1}{4}\pi\left(0.0127^2(m^2) - 0.0114^2(m^2)\right) = 2.41 * 10^{-5}(m^2),$$

$$m = \sqrt{\frac{11.8(W/m^2 * K) * 0.0399(m)}{382(W/m * K) * 2.41 * 10^{-5}(m^2)}} = 7.17(1/m),$$

and

$$\dot{Q} = \sqrt{11.8\left(\frac{W}{m^2 * K}\right) * 0.0399(m) * 382\left(\frac{W}{m * K}\right) * 2.41 * 10^{-5}(m^2)}$$
$$* \left(350(°C) - 20(°C)\right) \frac{cosh\left(7.17(m^{-1}) * 0.0762(m)\right) - \left[\frac{\left(50(°C) - 20(°C)\right)}{\left(350(°C) - 20(°C)\right)}\right]}{\sinh\left(7.17(m^{-1}) * 0.0762(m)\right)}$$

$$\dot{Q} = 40.2(W).$$

$\dot{Q} = 40.2(W)$ means that a 3 inch tall vertical copper pipe that cools from 350°C to 50°C via natural convection will transfer heat at a rate of 40.2 watts. The heat rate entering the system from the nichrome wire is 2.68 watts, giving this a factor of safety of $40.2(W)/2.68(W) = 15$. As such, requirement 10.3 is fulfilled.

The copper pipe can withstand 980 psia at 72°F (22°C) [7], having a factor of safety of $980(psia)/40.43(psia) = 24$. This value is large enough that any variation in copper's properties between 22°C and 350°C would not be an issue. As such, the copper pipe will not fail due to internal pressures.

The PTFE tubing can withstand 130 psia at 72°F (22°C) [10], having a factor of safety of $130(psia)/40.43(psia) = 3.2$. This tubing will be kept to a maximum of 50°C by the copper pipe's heat transfer capabilities, so this factor of safety is sufficient. As such, the PTFE tubing will not fail due to internal pressures.

Subsystem Verification Plans

Verification of subsystem requirements will be assessed via weighing the material storage before and after charging, operation of the fuel cell, the Bubble Test, and thermal imaging. A change in mass at the material storage indicates that hydrogen was stored, indicating that hydrogen was moved from electrolyzer to material storage. Operation of the fuel cell shows that hydrogen was moved from material storage to the fuel cell. Passing the Bubble Test both before and after operation demonstrates that the piping withstood the applied temperatures and pressures without leaking. Thermal imaging of the diverting valve during the extraction process will show whether the copper pipe was successful in transferring heat out of the system.

These verification plans can be performed in the same space and with the same tools as the other plans. Failure to transport hydrogen indicates a leak, which will be found using the Bubble Test. Failure to withstand temperatures and pressures will also be found using the Bubble Test. The locations of Bubble Test failures will be patched as necessary. Failure to convect away heat will result in a re-examination and possible redesign of the copper pipe.

Subsystem Summary

The piping subsystem transports hydrogen gas from the electrolyzer to the material storage and from the material storage to the fuel cell while withstanding applied temperatures and pressures. It is composed of one 0.5"OD x 0.45"ID x 3"long copper pipe and two 5/16"OD x 1/4"ID x 2'long PTFE tubes.

Interactive User Interface

Definition

The Interactive User Interface (IUI) includes all the visual aspects that the audience of the demonstrator see. This includes the pressure display, the mass of the storage system, any labels for measurements, a hydrogen economy infographic, as well as the final demonstrator of hydrogen creation using the electricity from the fuel cell. The value of this subsystem is to complete the demonstrator and allow the hydrogen process to be understandable to the viewers.

Requirements

The requirements for the IUI cover all requirements for educational aspects of the system. This includes having labeled components, displaying the flow rate of hydrogen as well as how much hydrogen gas has been produced, including a learning feature about the hydrogen economy, and that all values must be displayed in English units. In addition to the system requirements,

11.1 The system must include a pressure gauge integrated in the hydrogen piping directly after the electrolysis.
11.2 The system must include a scale to mass the material storage subsystem.
11.3 The IUI must have an infographic detailing the hydrogen production methods, storage methods, and uses.
11.4 The IUI must have displays to indicate all measured values.
11.5 The IUI displays must display values with English units.

Requirement 11.1 supports system requirement 3.2 outlining that there will be a pressure gauge to detect a change in pressure in the hydrogen piping, indicating production of hydrogen.

Requirement 11.2 supports system requirement 3.3 by detecting the change in mass in the storage system before and after hydrogen loading using the scale required by this subsystem requirement.

Requirement 11.3 supports system requirement 3.1.3 by using an infographic as the demonstrator's learning feature. This infographic displays the different production, storage, and use cases for hydrogen.

Requirement 11.4 and 11.5 support system requirement 3.1.4 which requires the measured values to be displayed in English units. In order to allow the viewers to make sense of the demonstrator, the measured values must be displayed to the user. Since most viewers would be familiar with the English unit system, this allows the most users to understand the measurements.

Governing Equations

The governing equations for the IUI consist of methods of measuring flow and measuring the mass of hydrogen throughout the material storage system. The main governing equation for the pressure gauge is the Ideal Gas Law, equation number 22 below.

$$PV = mRT \tag{22}$$

Where:

P = Absolute Pressure of gas (KPa)
V = Volume of gas (L)
m = Mass of gas (g)
R = Ideal gas constant (KJ/Kg*K), Hydrogen = 4.124 KJ/Kg*K
T = Absolute temperature of gas (K)

Using this equation, we can read the pressure given on the pressure gauge, and assuming a constant volume that we are measuring and a constant temperature, we can calculate how many grams of hydrogen are present within the section of our system. This can be used to measure a production rate of the electrolysis unit so we can verify our production requirements. This can also be used to verify when the material storage is full, as the pressure in the system would begin to rise again.

Subsystem Verification Plans

To verify the effectiveness of the IUI, ERH2 will conduct a verification test. A group with no background knowledge will be brought in to view the project and gather feedback afterwards. This allows ERH2 to verify that the project is understandable and serves its main role as an educational demonstrator. If the results indicate that the system is not an effective demonstrator, plans will be developed to determine what can be improved to increase the effectiveness.

Subsystem Summary

The IUI is a critical subsystem of our project because it allows the audience to fully understand what the system is doing. Without the measurement displays or the final hydrogen gas demonstrator, it would make it very difficult for the audience to understand what is happening. Because hydrogen gas is not visible to the human eye, the Interactive User Interface includes a pressure gauge, a scale, a hydrogen demonstrator, and measurement readouts all in English units, to allow the audience to understand where there is hydrogen in the system and try to understand how much there is.

Conclusion

The ERH2 demonstrator consists of six subsystems that create and store hydrogen to run the ERAU fuel cell.

Acknowledgements

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Appendix

Appendix A: Requirements

1.0 Function

1.1 The system must produce hydrogen gas.
1.1.1 The system must produce at least 0.02 grams of hydrogen gas to run the fuel cell for 10 minutes at 1 watt.
1.2 The system must store 0.04 grams of hydrogen gas.
1.3 The system must use DC power to be able to use both alternative energy sources and battery power.

2.0 Safety

2.1 The system must allow for safe extraction of hydrogen gas without risk of major leaks.
2.2 The system must follow Embry-Riddle Prescott Campus' safety requirements.
https://myerauedu.sharepoint.com/teams/APPM/section-2/Pages/2-4-policy.aspx

3.0 Educational

3.1 The internal system components should be visible.
3.2 The system must detect the production of hydrogen gas.
3.3 The system must display the approximate amount of hydrogen gas stored.
3.4 The system must have a learning feature about the hydrogen economy and where it could go in the future.
3.5 The system must display all values used for demonstration purposes in English units.

4.0 Performance

4.1 The material storage efficiency (hydrogen in vs. hydrogen out) must be at least 50%.
4.2 The system must weigh less than 25 pounds dry.
4.3 The material storage to fuel cell system must be able to run for 10 minutes.
4.4 All subsystem interfaces must be sealed.

5.0 Human Factor

5.1 The system must operate in a room that has a fire/smoke alarm system if working indoors.
5.2 The system should have a simple on/off switch for operation.

6.0 Electrolysis

6.1 The operating pressure of the electrolysis system must be less than or equal to 0.29psi gauge pressure.
6.2 The hydrogen and oxygen produced in the electrolysis system must not mix.
6.3 The electrolysis system housing layers must be replaceable.
6.4 The electrolysis system housing must be resealable.
6.5 The electrolysis system housing must not be electrically conductive.
6.6 All wires must be insulated and sized according to the National Electrical Code.
6.7 The amperage applied to the electrolysis system must not exceed 20 amps.
6.8 The electrolysis system must have an emergency kill switch.

7.0 Material Storage
7.1 Material storage must release hydrogen at 0.02 grams every 10 minutes.
7.2 Material must store hydrogen with at least 2% weight of hydrogen gas.
7.3 Must produce at least 0.4 grams of material storage.

8.0 System Integration
8.1 All interfaces at the electrolyzer will be properly accounted for and sized.
8.2 All interfaces at the pressure gauge interface will be properly accounted for and sized.
8.3 All interfaces at the material storage interface will be properly accounted for and sized.

9.0 Heating
9.1 The heating system must cause the material storage to release hydrogen.
9.2 The heating system must heat the storage material to 300°C and must not exceed 350°C.

10.0 Piping
10.1 The subsystem must transport hydrogen gas from the electrolyzer to the material storage, and from the material storage to the fuel cell.
10.2 The subsystem must withstand internal pressures up to 40.43psi absolute without leaking.
10.3 The subsystem must withstand temperatures up to 350°C without leaking.

11.0 Interactive User Interface
11.1 The system must include a pressure gauge integrated in the hydrogen piping directly after the electrolysis.
11.2 The system must include a scale to mass the material storage subsystem.
11.3 The IUI must have an infographic detailing the hydrogen production methods, storage methods, and uses.
11.4 The IUI must have displays to indicate all measured values.
11.5 The IUI displays must display values with English units.

Appendix B: Design Team Organization Chart

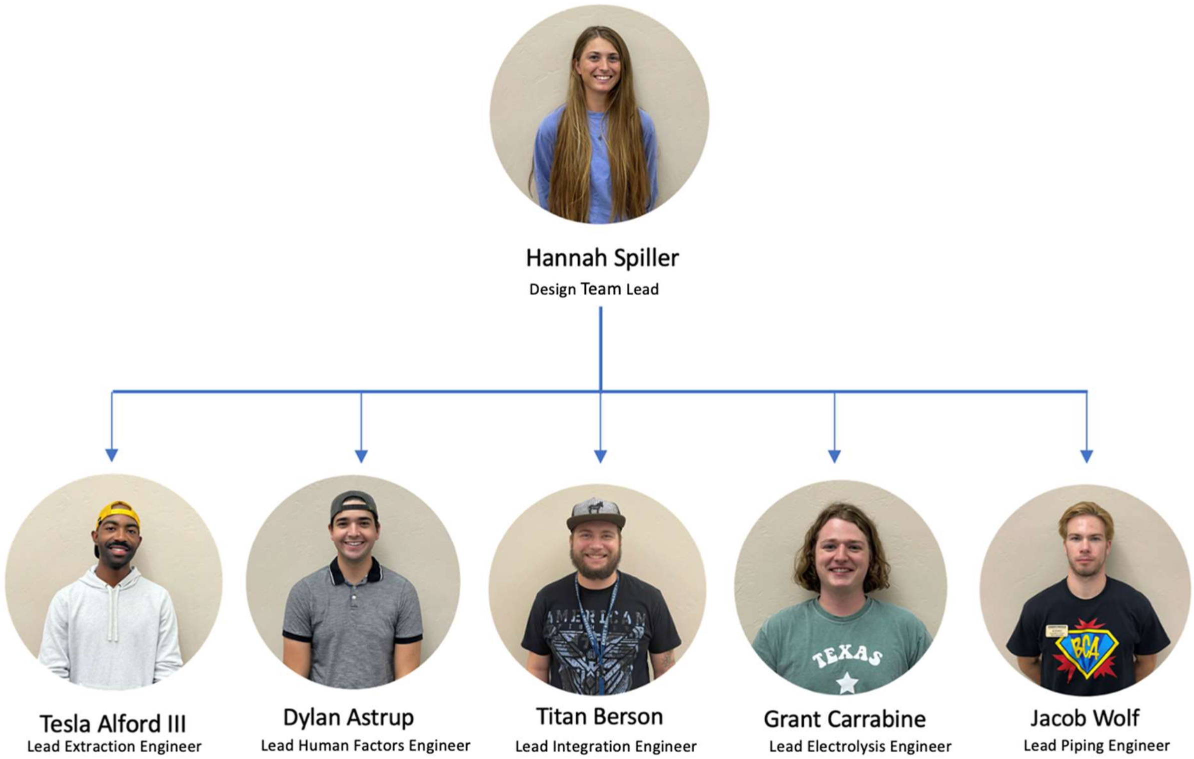

Figure 17: Design Team Organization Chart

Appendix C: Budget

Table 22: Itemized Budget Table

Item	Cost
Shirts	$150.00
Urea	$20.00
lithium Chloride 30grams	$17.90
Plexiglass	$84.56
Pressure gauge	$35.65
Mesh X 2	$22.00
PTFE Tubing x 25ft	$62.25
F-F Thread Adapter x2	$19.12
Bolts	$7.60
Copper Pipe (2ft)	$5.49
Barbed T fitting x 2	$24.28
Barbed Fitting x3	9.02
Graduated Bottle	91.64
Nichrome Wire 20gauge x 50ft	$12.00
Solder	$30
Rubber Plug	$10.42
Rubber Tape (25ft)	18.37
Diverting Valve	123.84
Epoxy's	$30
nuts	$2.20
Other Plastic	$88.04
Power Supply	$289.99
Total	

$1,154.37

Appendix D: Schedule

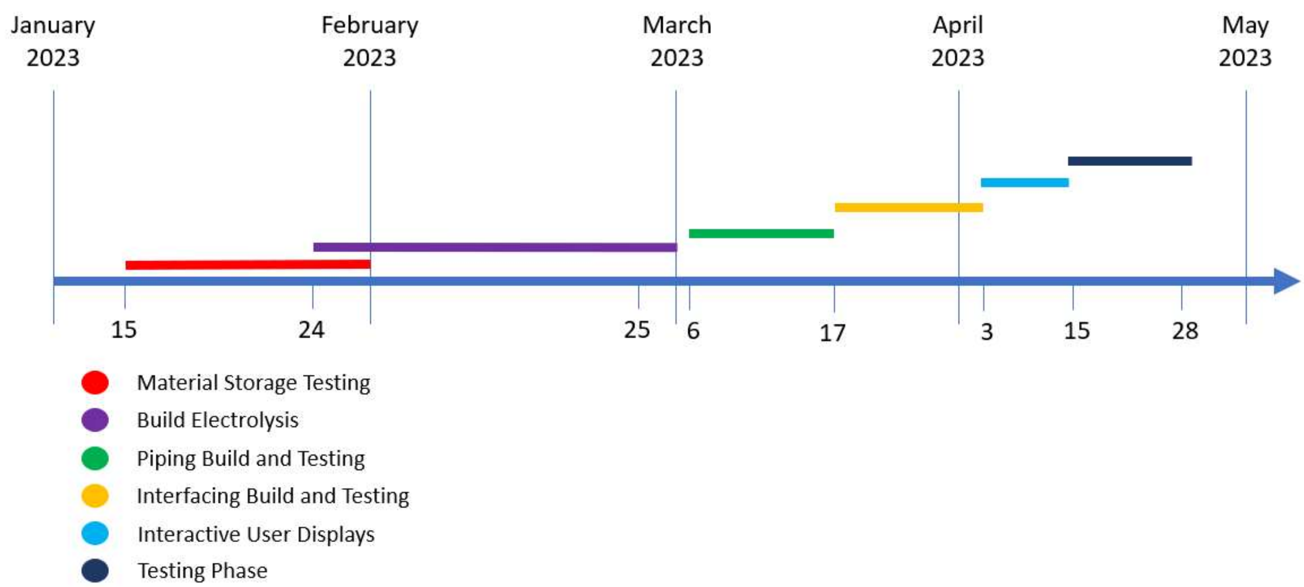

Figure 18: Detail semester schedule

Appendix E: Requirement Verification Matrix

Table 33: Requirement Verification Matrix

Requirement			Design Metric	Verification Method
Number	**Title**	**Description**		
1.0	Function			
1.1		The system must produce hydrogen gas	Alkaline Selection	Test
1.1.1		The system must produce 0.02 grams of hydrogen gas to run the fuel cell for 10 minutes at 1 watt.	Electrolysis Design	Test
1.2		The system must store 0.04 grams of hydrogen gas.	Material Volume	Test
1.3		The system must use DC power to be able to use both alternative energy sources and battery power.	System Design	Test
2.0	Safety			
2.1		The system must allow for safe extraction of hydrogen gas without risk of major leaks.	Sealant	Test
2.2		The system must follow Embry-Riddle Prescott Campus' safety requirements. https://myerauedu.sharepoint.com/teams/APPM/section-2/Pages/2-4-policy.aspx	System Design	Inspection
3.0	Educational			
3.1		The system must serve as an educational demonstrator or lab device for the student body of Embry Riddle Prescott campus.	System Design	Inspection
3.1.1		The internal system components should be visible for educational purposes.	System Design	Inspection
3.1.2.1		The system must detect the production of hydrogen gas.	System Design	Inspection
3.1.2.2		The system must display the approximate amount of hydrogen gas stored.	System Design	Inspection
3.1.3		The system must have a learning feature about the hydrogen economy and where it could go in the future.	System Design	Inspection
3.1.4		The system must display all values used for demonstration purposes in English units.	System Design	Inspection

4.0	Performance			
4.1		The material storage efficiency (hydrogen in vs. Hydrogen out) must be at least 50%.	Material Volume	Test
4.2		The system must weight less than 25 pounds dry.	System Design	Inspection
4.3		The material storage to fuel cell system must be able to run for 10 minutes.	Material Volume	Test
4.4		All subsystem interfaces should have a proper connection.	User Interface	Inspection
5.0	Human Factor			
5.1		The system must operate in a room that has a fire/smoke alarm system if working indoors.	System Location	Inspection
5.2		The system should be easy to operate by authorized users.	User Interface	Inspection
		Subsystem Requirements		
6.0	Electrolysis			
6.1		The hydrogen and oxygen produced in the electrolysis system must not mix.	Membrane Design	Test
6.2		The electrolysis system housing layers must be replaceable.	System Design	Demonstration
6.3		The electrolysis system housing must be resealable.	System Design	Demonstration
6.4		The electrolysis system housing must not be conductive.	Material Selection	Analysis; Test
6.5		All wires must be insulated and sized according to the National Electrical Code.	System Design	Inspection
6.6		The amperage applied to the electrolysis system must not exceed 20 amps.	Applied Power	Analysis; Test
6.7		The electrolysis system must have an emergency kill switch.	System Design	Inspection; Demonstration
7.0	Material Storage			
7.1		Material storage must release hydrogen at 0.02 grams every 10 minutes.	Steady state Temperatur e	Test
7.2		Material must store hydrogen with at least 2% weight of Hydrogen.	Material Compositio n	Test

7.3		Must produce at least 0.4 grams of material storage.	Material Volume	Test
8.0	System Integration			
8.1		All interfaces at the electrolyzer will be properly accounted for and sized.	Sealant	Test
8.2		All interfaces at the pressure gauge interface will be properly accounted for and sized.	Sealant	Test
8.3		All interfaces at the material storage interface will be properly accounted for and sized.	Sealant	Test
9.0	Extraction			
9.1		The heating system must be able to cause the material storage to off-gas hydrogen at a rate which yields a gauge pressure less than 2000pa or 0.29psi.	Steady state Temperatur e	Test
9.2		The heating system must be able to heat the storage material to 300°c and must not exceed 350°c.	Applied Power	Test
10.0	Piping			
10.1		The subsystem must transport hydrogen gas from the electrolyzer to the T-fitting, and from the T-fitting to the fuel cell.	System Design	Test
10.2		The subsystem must withstand internal pressures up to 0.29psi gauge without leaking.	Material Choice	Test
10.3		The subsystem must withstand temperatures up to 350°C without leaking.	Material Choice	Test
11.0	Interactive User Interface			
11.1		The system must include a pressure gauge integrated in the hydrogen piping directly after the electrolysis.	System Design	Inspection
11.2		The system must include a scale to mass the material storage subsystem.	System Design	Inspection
11.3		The IUI must have an infographic detailing the hydrogen production methods, storage methods, and uses.	System Design	Inspection

11.4	The IUI must have digital displays to indicate all measured values.	System Design	Inspection
11.5	The IUI displays must display values with English units.	System Design	Inspection