Electrolysis and Material Storage of Hydrogen Gas

pt. 2

ERH2

EMBRY-RIDDLE HYDROGEN

Embry-Riddle Needs Hydrogen Energy Demonstrators

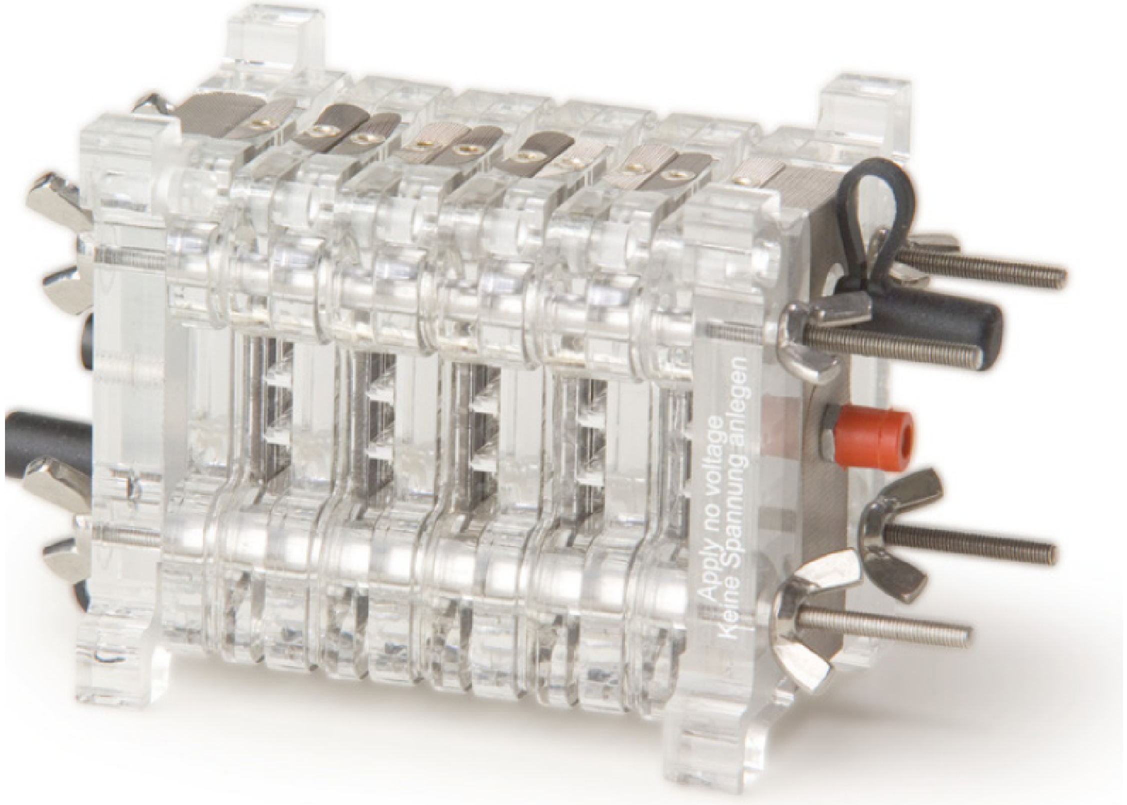
Develop Energy Labs

Create Interest in the Energy Track

Viewable Demonstrations for Visitors

Generate and Store Hydrogen

ERH2's purpose is to create an energy demonstrator to generate and store hydrogen.



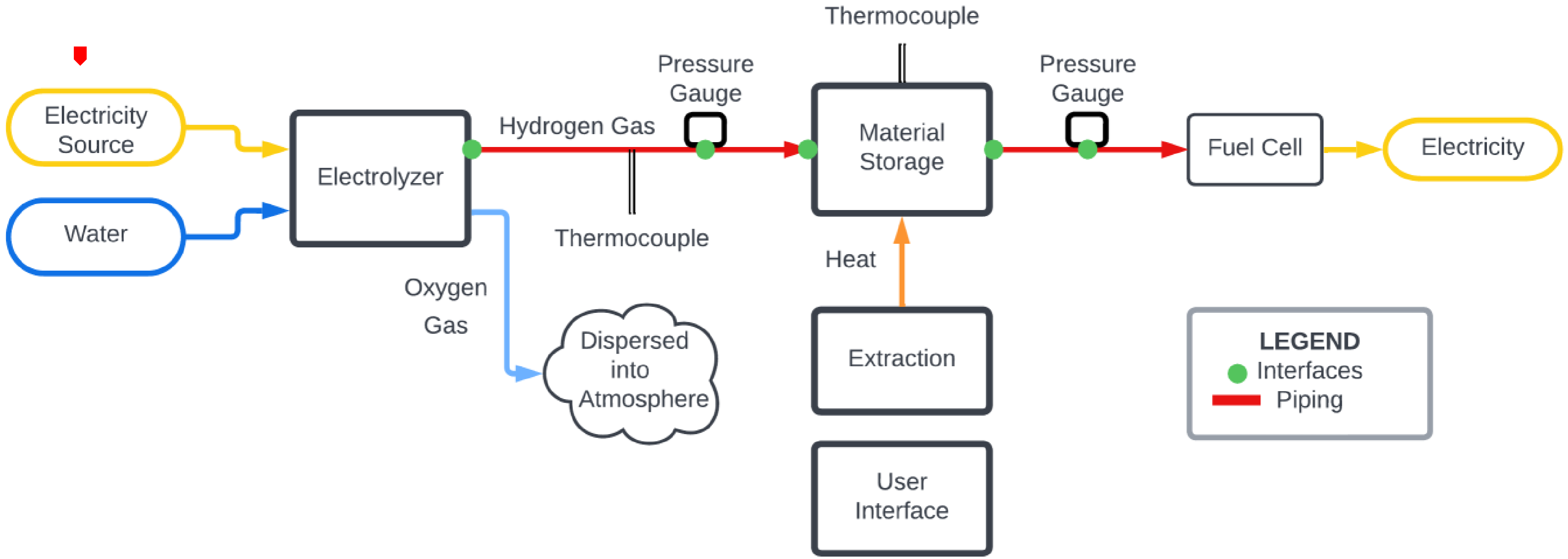
Embry-Riddle's Fuel Cell

ERH$_2$

System Requirements

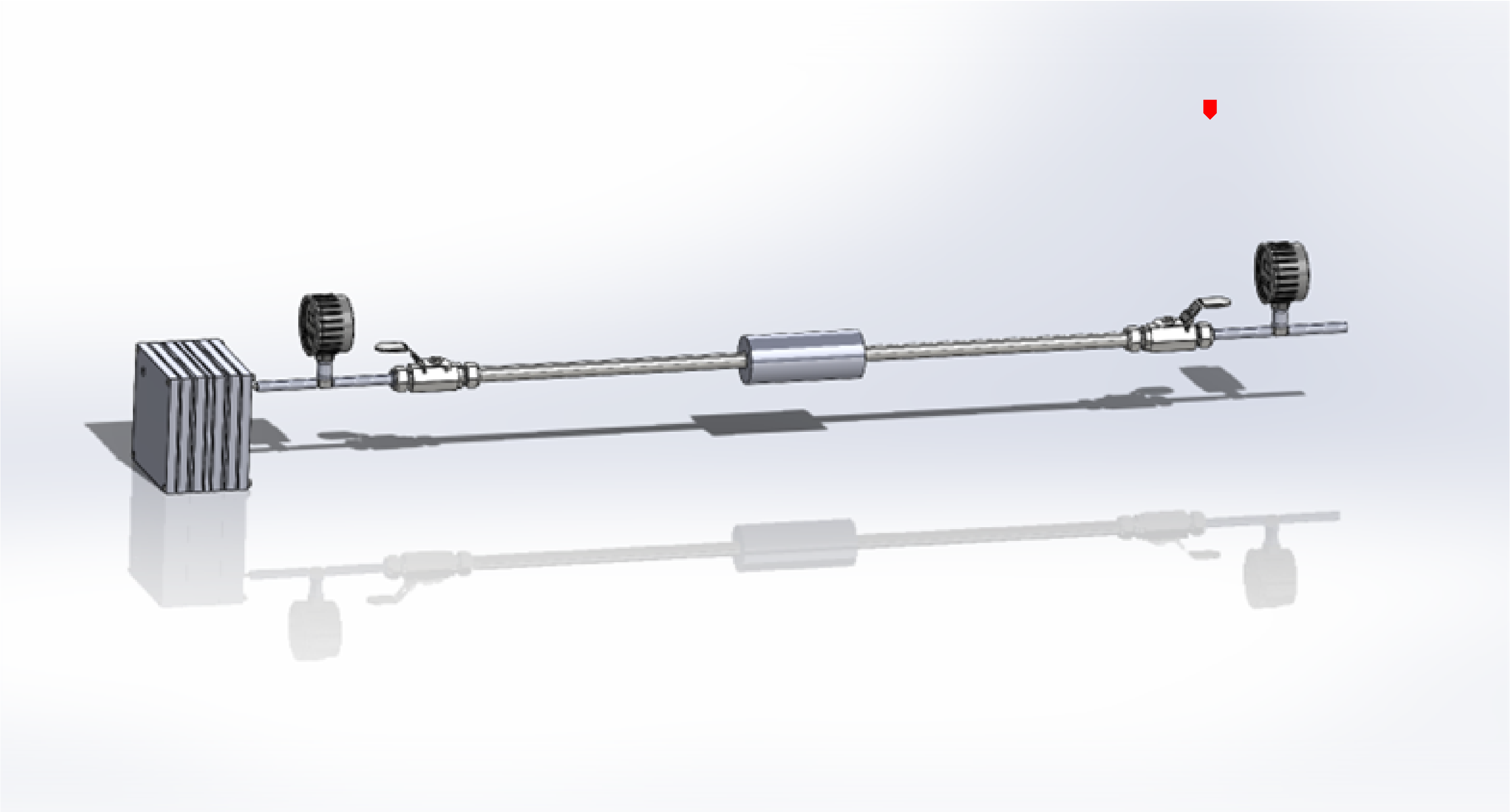
- 1.1 The system must produce hydrogen gas.
- 1.1.1 The system must produce enough hydrogen to get the fuel cell to steady state and then run for 10 minutes at 1 watt.
- 1.1.2 The system must be able to determine the rate of hydrogen gas produced.
- 1.2 The storage method must run the fuel cell for a minimum of 5 minutes.
- 1.2.1 The system must measure the amount of hydrogen stored.
- 1.3 The system must fit into a 4’x2’ box.
- 1.4 The system must interface with the Embry-Riddle fuel cell.
- 1.4.1 The system output must be a ¼” PTFE tube.

Process Flow Diagram



Simplified PFD

ERH2 Proposed System



Concept of Operations

Step 1: Weigh the material storage capsule using scale and record mass.

Concept of Operations

Step 2: Insert the material storage capsule using measurement rod to ensure the capsule is in the heating zone.

Concept of Operations

Step 3: Attach copper pipe to yor-lock valve until wrench tight.

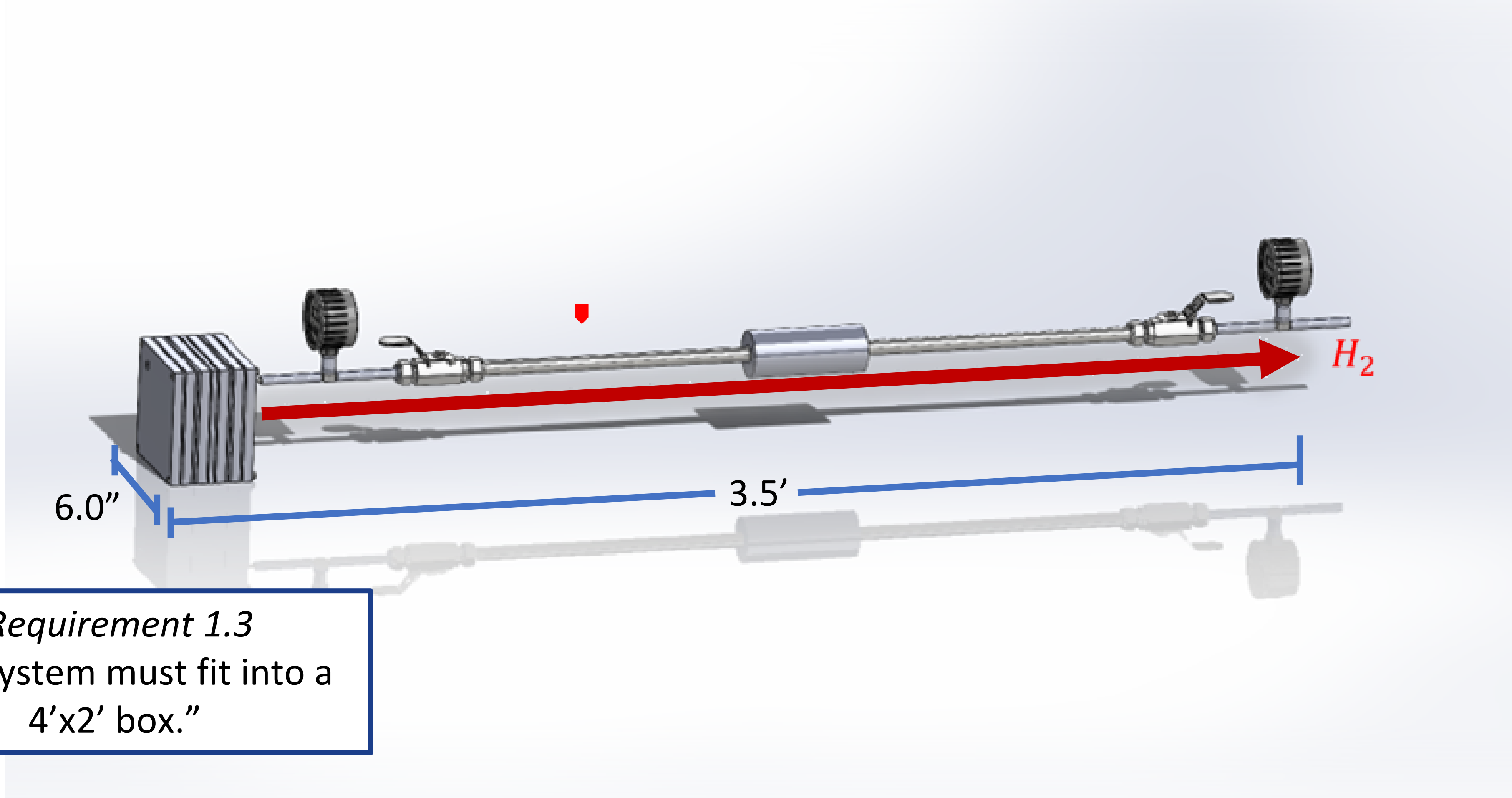
Concept of Operations

Step 4: Ensure all valves are open, turn on the electrolysis machine, and run until the fuel cell light comes on.

Concept of Operations

Step 5:

The ERH2 System

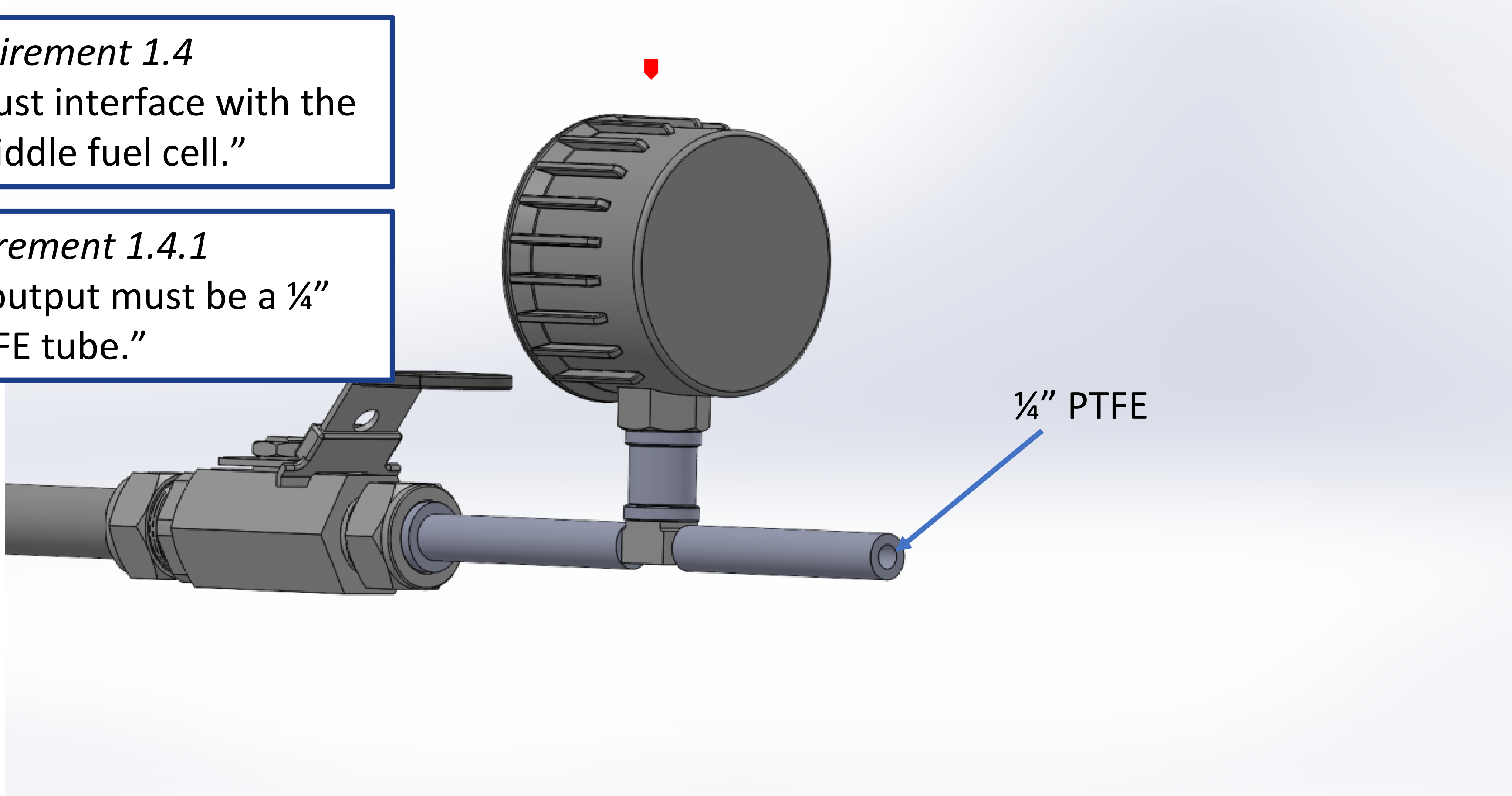


Requirement 1.3
“The system must fit into a 4’x2’ box.”

Fuel Cell Integration

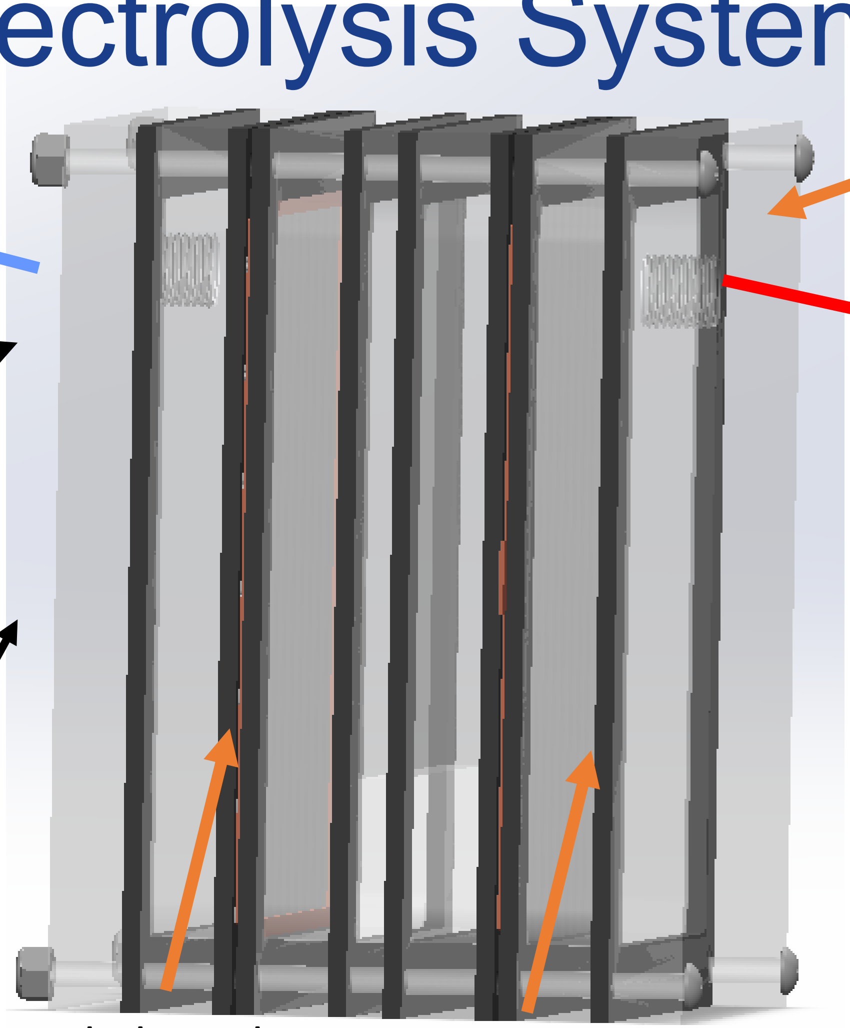
Requirement 1.4
"The system must interface with the Embry-Riddle fuel cell."

Requirement 1.4.1
"The system output must be a ¼" PTFE tube."



Electrolysis

ERH2's Electrolysis System



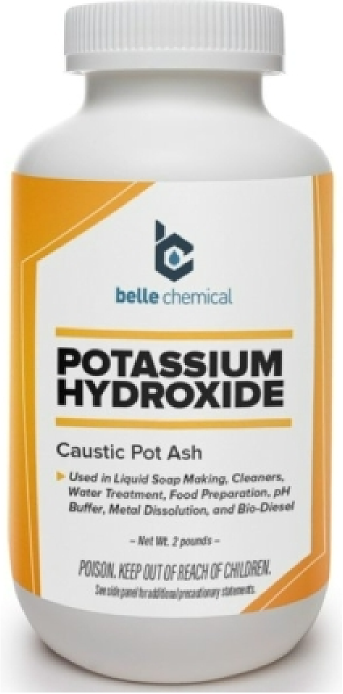
Model of ERH2's planned Electrolyzer

Requirement 3.1
"The system must be able to be dissembled and reassembled to replace parts."

Requirement 3.3
"The machine components must not be embrittled by hydrogen."

Alkaline Water

- Made from Potassium hydroxide (KOH)
- Typical solution is 32% to 50% in strength [6]
- Our system will use a solution of 35%
- 350g KOH into 1 Liter of water



Alkaline Water Electrolysis

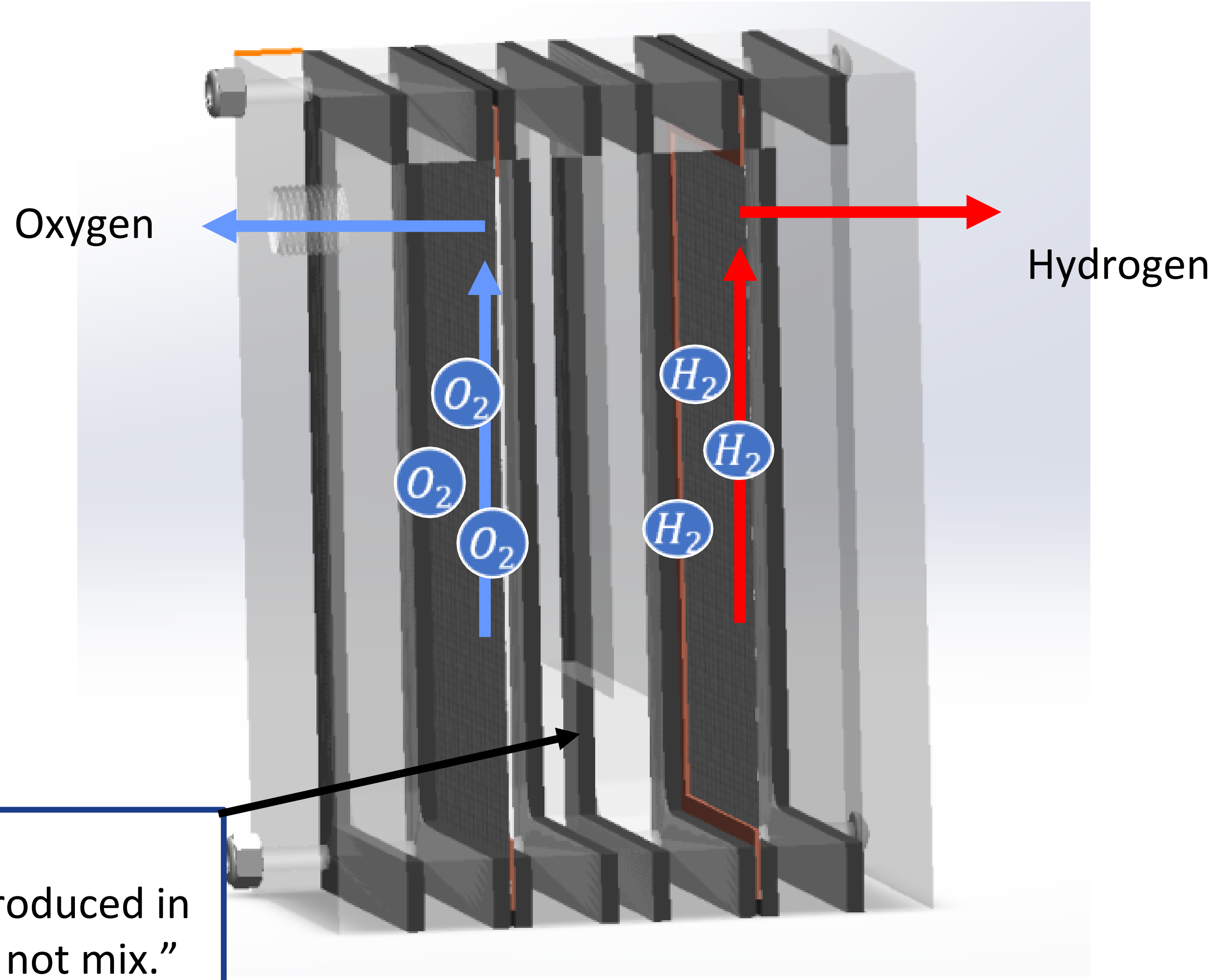
Cathode: $$2H_2O + 2e^- \xrightarrow{yields} H_2 + 2OH^-$$

Anode: $$2OH^- \xrightarrow{yields} \frac{1}{2}O_2 + H_2O + 2e^-$$

[5]

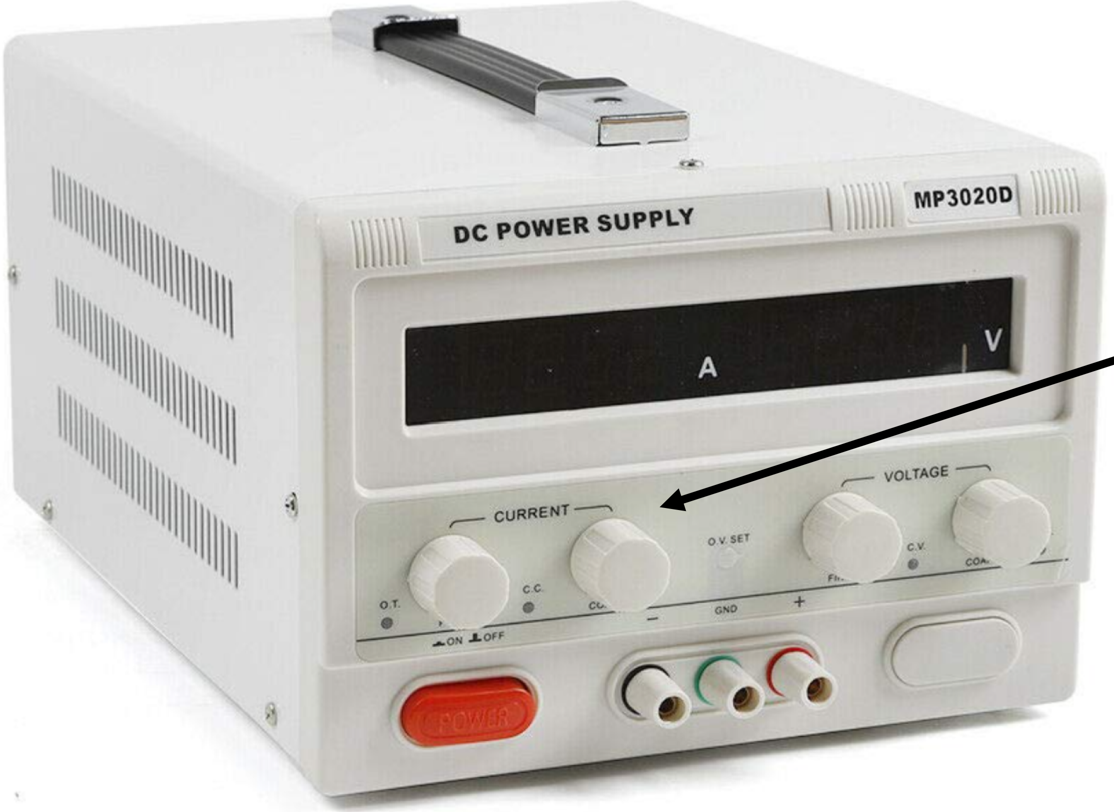
ERH2

Mesh Section-View



Requirement 3.2
"The hydrogen and oxygen produced in the electrolysis system must not mix."

Power Supply



Requirement 3.4
"The amperage going into the system must be controlled and limited to 22.89 amps."

Estimate of Hydrogen Needed

$$\frac{Power\ wanted(kW) * Time(sec.)}{Percent\ Eff\ of\ fuel\ cell * Lower\ heating\ value\left(\frac{KJ}{Kg}\right)} = Amount\ needed(g\ H_2)$$

$$\frac{.001kW * 600\ (sec.)}{0.25 * 120{,}000\left(\frac{KJ}{Kg}\right)} = \boxed{.02\ (g\ H_2)}$$

Faraday's Law of Electrolysis

Rate of H2 Production

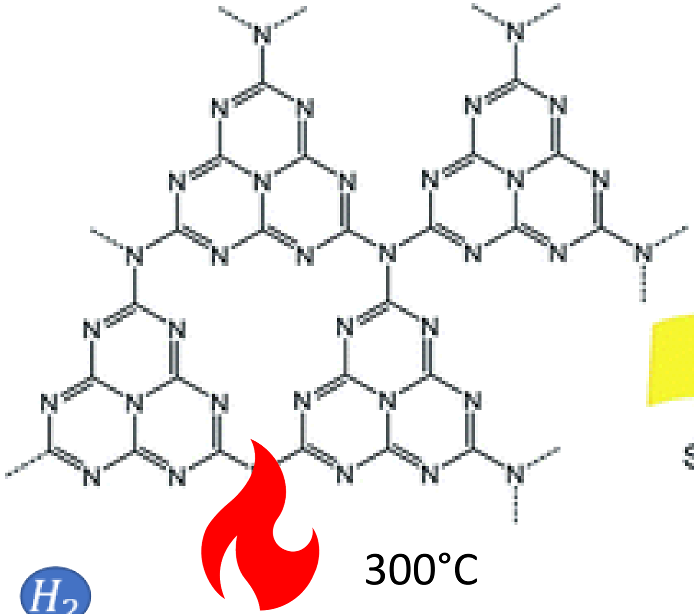
$$\frac{Max\ theoretical\ Current}{Valence} * Molar\ weight\ of\ H$$

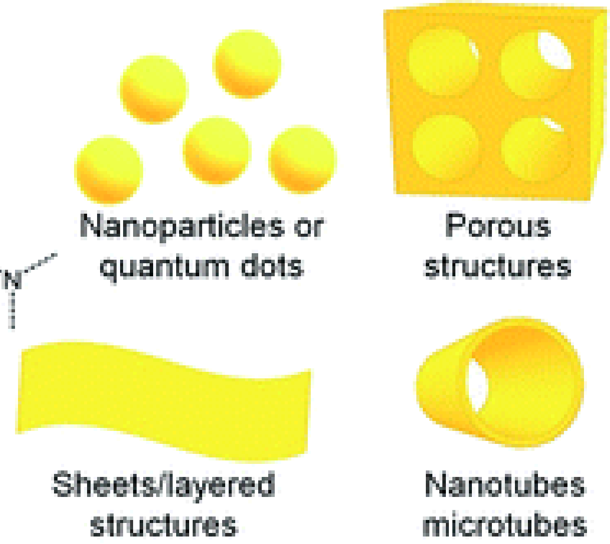
$$\frac{20\ (C)}{1\ (s)} * \frac{600\ (s)}{96{,}485\ (C)} * \frac{1\ (mol\ H_2)}{2\ (mol\ e^-)} * \frac{2.007\ (g\ H_2)}{1\ (mol\ H_2)} = \boxed{0.125\ (g/10min\ H_2)}$$

Requirement 1.1.1
"The system must produce enough hydrogen to get the fuel cell to steady state and then run for 10 minutes at 1 watt."

Material Storage

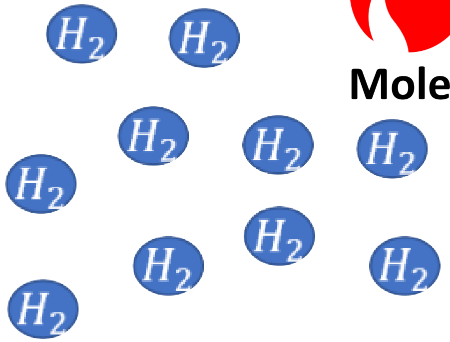
Lithium-Doped Graphitic Carbon Nitride $[Li_2C_4N_3/ Li_2C_4N_4]$





300°C

Molecular Level



Material Capacity

"…it was found that the gravimetric and volumetric densities of hydrogen in both $Li_2C_4N_3$ and $Li_2C_4N_4$ were greater than 10 wt% and 100 g/L respectively" [1].

1 g $Li_2C_4N_3$

Requirement 4.4
"Material must store hydrogen with at least 2% weight of hydrogen gas."

$$\%_{wtH_2} = \frac{m_{H_2Stored}}{m_{final}} * 100$$

$$m_{H_2Stored} = m_{final} - 1$$

Requirement 1.2
"The material storage must run the fuel cell for a minimum of 5 minutes."

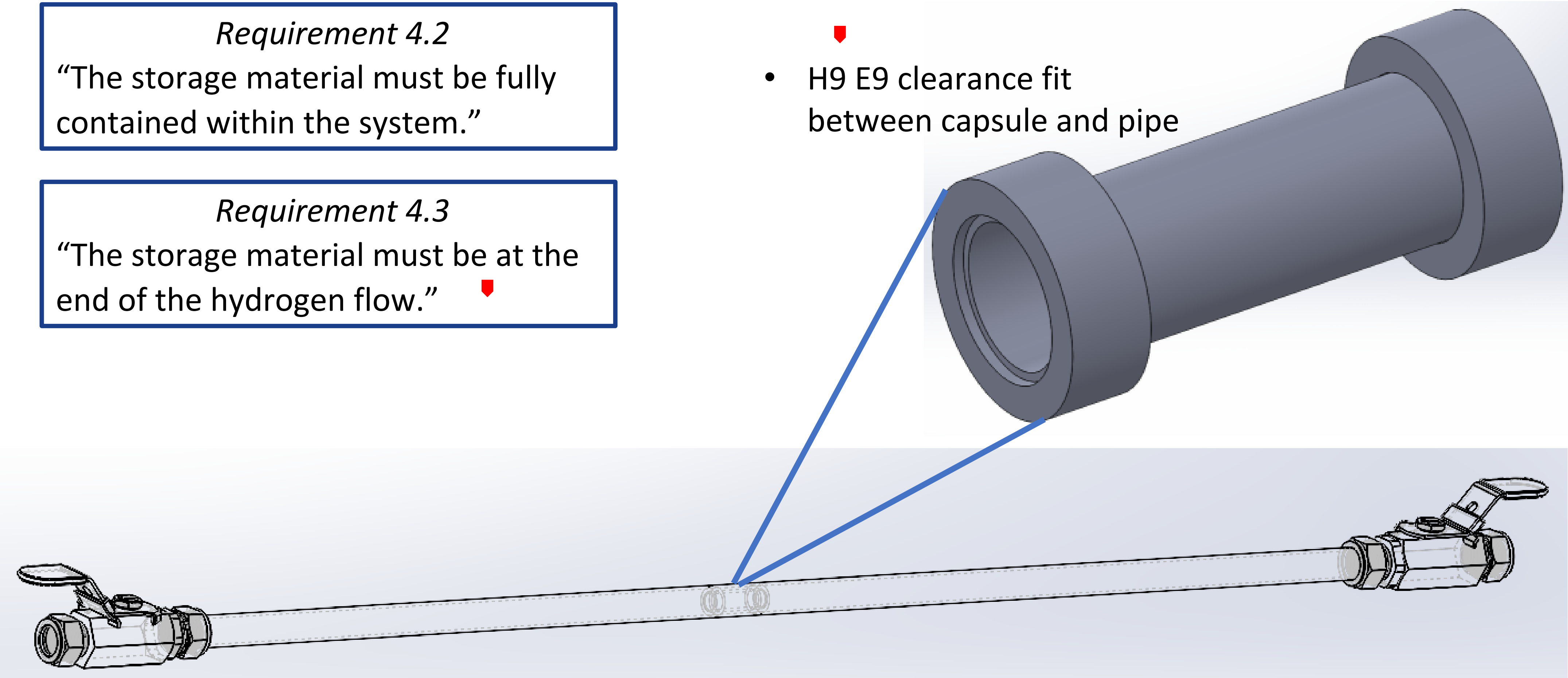
CIPET सिपेट
probe · perform · practice · Plastics

Material Integration

Requirement 4.2
"The storage material must be fully contained within the system."

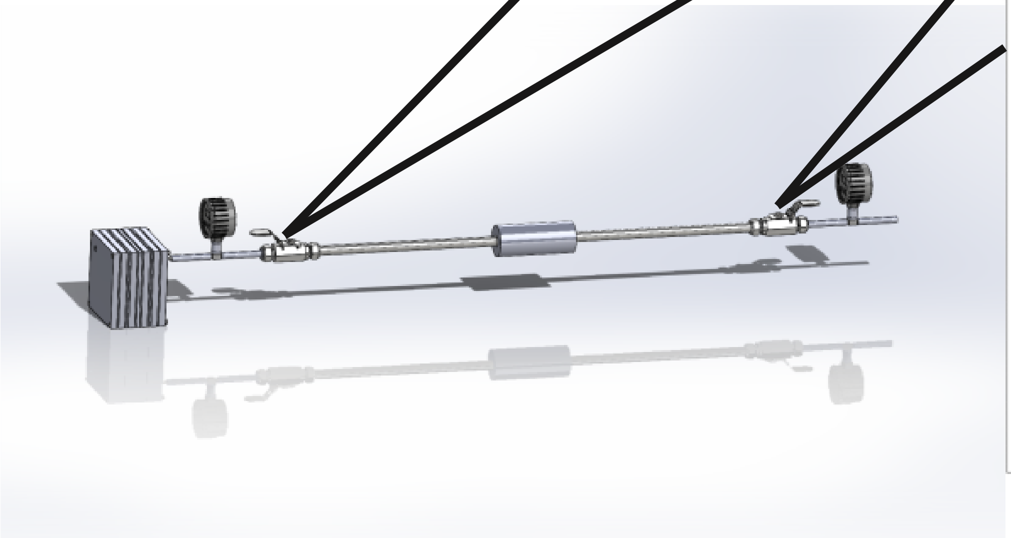
Requirement 4.3
"The storage material must be at the end of the hydrogen flow."

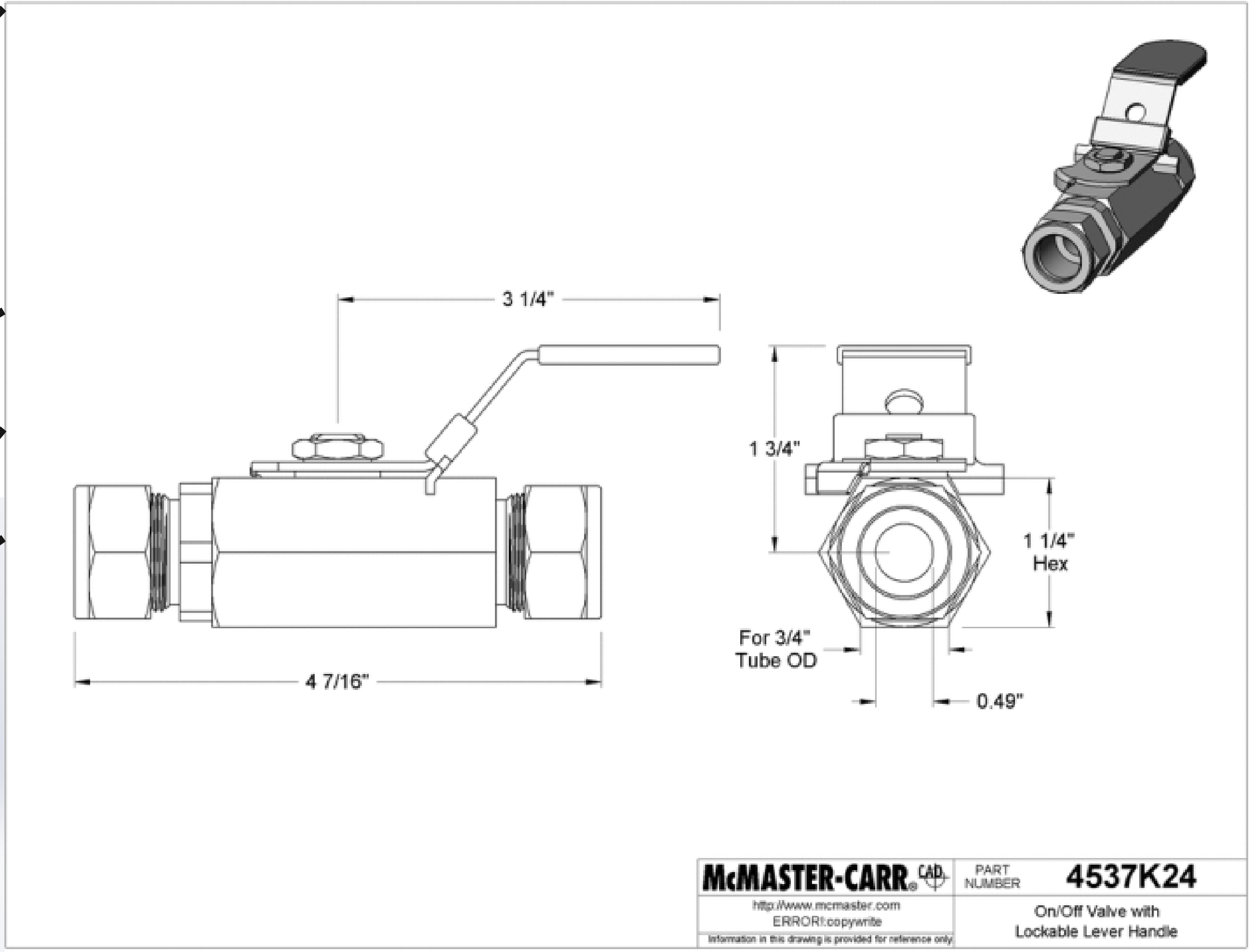
- H9 E9 clearance fit between capsule and pipe



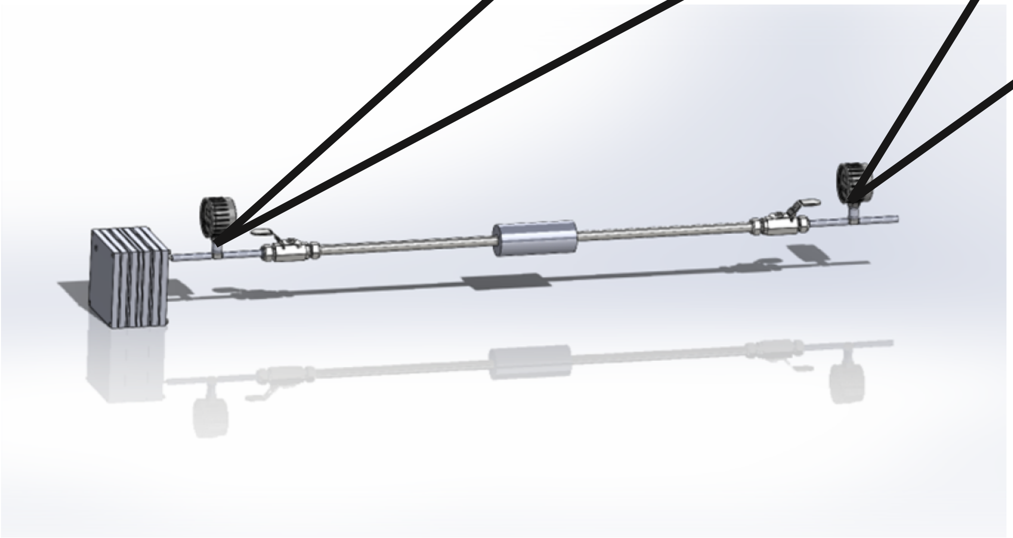
Interfaces

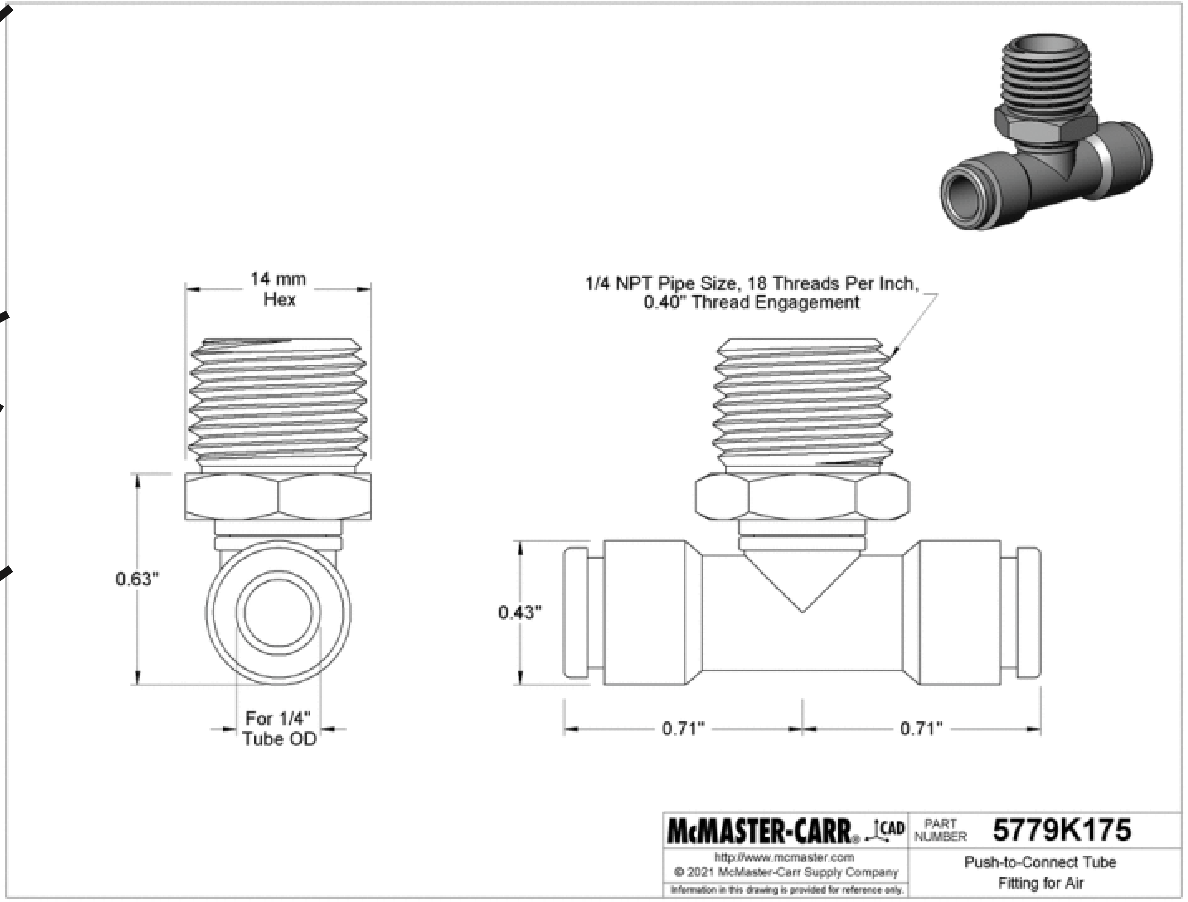
Interfaces - Valves



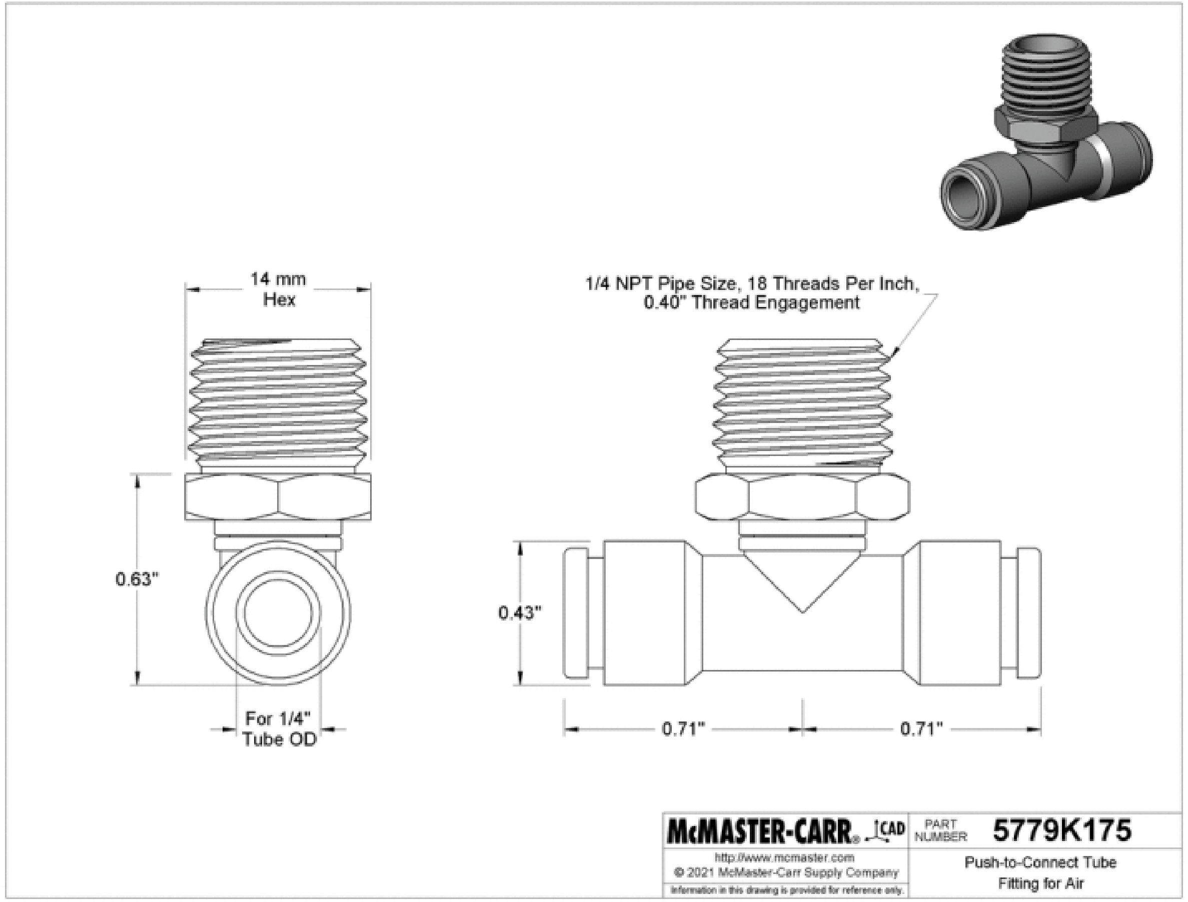


Interfaces – Tee Fittings

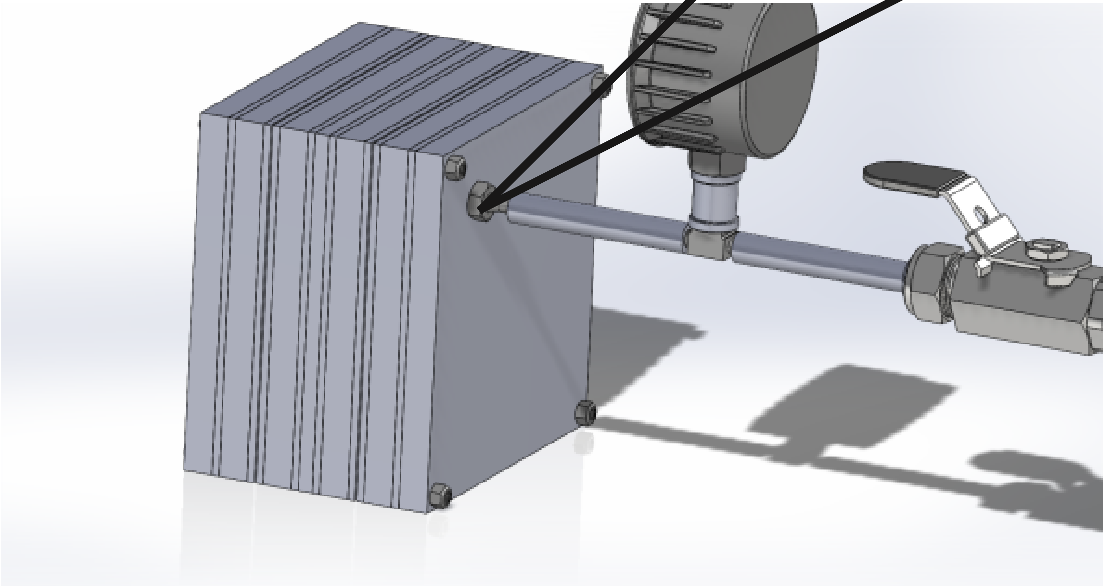


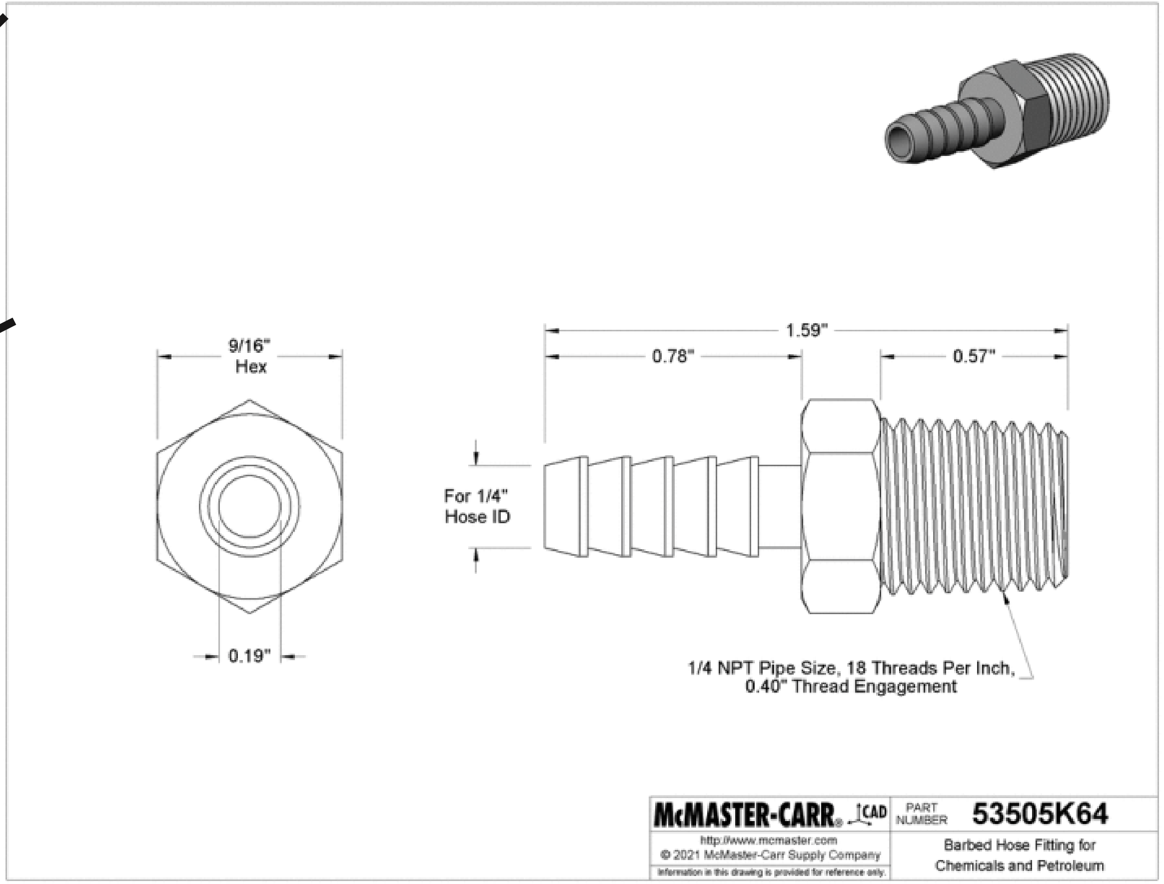


Interfaces – Tee Fittings Con.



Interfaces – Electrolyzer Fitting





Piping

Adiabatic Fin Tip – Best Heat Transfer Model

Compare stainless steel pipe to hydrogen gas:

- How much energy will each material release in a 350°C to 50°C temperature drop, on a per-unit-length basis?

Temperature Start	350	(°C)	
Temperature End	50	(°C)	
Temperature Change:	300	(°C)	
	Pipe	Hydrogen	
Cross-Sectional Area	5.07E-05	2.34E-04	(m^2)
Specific Heat	468	14500	(J/kg*K)
Density	7500	0.076	(kg/m^3)
Energy	53410	77	(J/m)
Pipe/Hydrogen Energy Ratio	690		

- Thermal energy in hydrogen is negligible compared to thermal energy in steel.
- Negligible heat transfer at the end of the pipe.
    - 50°C pipe to 20°C air.

Treat the pipe as a fin with an adiabatic tip.

Adiabatic Fin Treatment

Adiabatic fin tip:

$$\frac{T(x) - T_\infty}{T_b - T_\infty} = \frac{\cosh m(L - x)}{\cosh mL}$$

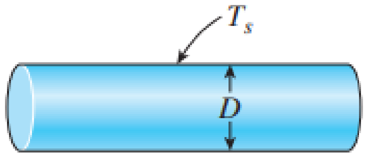
$$m^2 = \frac{hp}{kA_c}$$

Solve for length L

Known:
- P perimeter
- k thermal conductivity
- Ac cross-sectional area
- T temperatures

Unknown:
- h convection coefficient

Finding Convection in the Worst-Case Scenario: Only Natural Convection

Horizontal cylinder 	D	$Ra_D \leq 10^{12}$	$Nu = \left\{0.6 + \dfrac{0.387 Ra_D^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}}\right\}^2$	**(9–25)**

This is for isothermal cylinders. Do analysis at max and min temp		
Outer Diameter:	0.75	(in)
Inner Diameter:	0.68	(in)
Thermal Conductivity	20	(W/m*K)
Surface Temperature (max)	350	(°C)
Surface Temperature (min)	50	(°C)
Outer Diameter	0.01905	(m)
Gravitational Constant	9.81	(m/s^2)
Bulk Temperature	20	(°C)

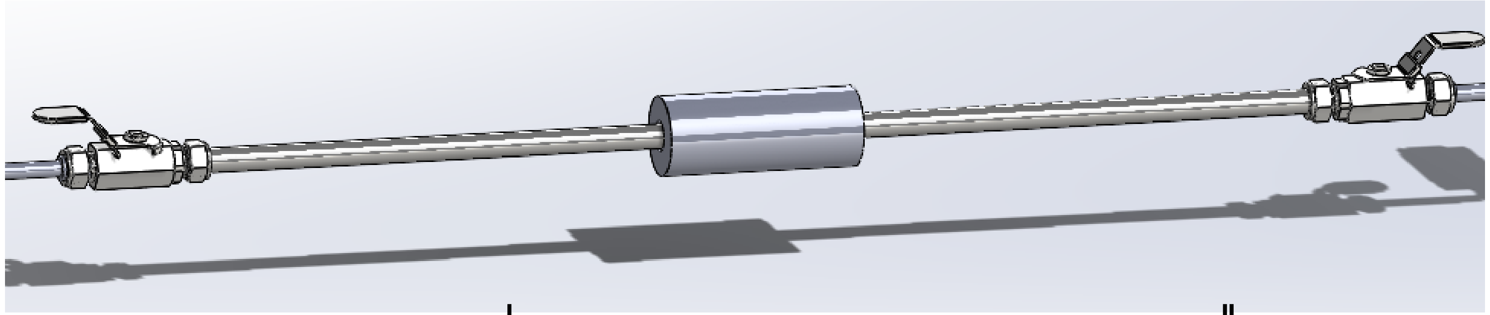
	At Max Temp	At Min Temp	
Volume Expansion Coefficient	2.18E-03	3.27E-03	(K^-1)
Kinematic Viscosity	3.26E-05	1.66E-05	(m^2/s)
Grashof Number	4.59E+04	2.43E+04	
Prandtl	0.69884	0.7268	
Rayleigh	3.21E+04	1.76E+04	
*Rayleigh < 10^12, we can use the book's equation!			
Nusselt Number	5.8	5.0	
Thermal Conductivity (H2)	0.0367	0.0263	(W/m*K)
Convection Coefficient	11.2	6.9	(W/m^2*K)

$$Gr_L = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2} \qquad Ra_L = Gr_L Pr \qquad Nu = \frac{hL_c}{k}$$

Calculating Required Length

At the tip: $\cosh(m(L-L)) = \cosh(0) = 1$, $\cosh(mL) = \frac{T_b - T_\infty}{T_L - T_\infty} = x$, $mL = cosh^{-1}(x)$, $L = cosh^{-1}(x)/m$

Inner Diameter	0.0173	(m)
Perimeter	0.0598	(m)
Cross-sectional Area	5.07214E-05	(m^2)
x	11	
Convection Coefficient, Avg	9.06	(W/m^2*K)
m	2.31E+01	
cosh^-1(x)	3.09	
Length	0.134	(m)
	5.3	(in)



5.3 (in) 5.3 (in)

Extraction

Heating Element – Nichrome Wire

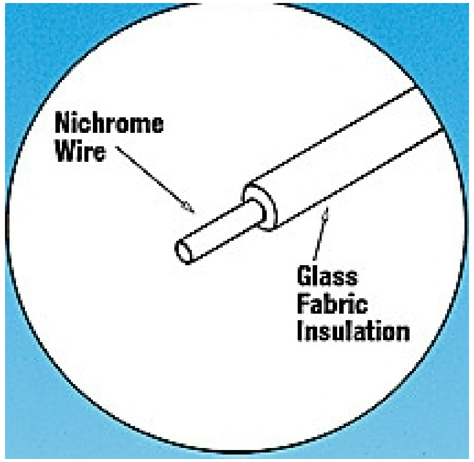
Requirement 4.1
"The storage material must be heated to 300 degrees Celsius and not exceed 350 degrees Celsius."

Target Temperature for H_2 Release: 300°C

Wire Resistance: 2.1Ω/ft.
Wire Diameter: 1mm (.04 in)

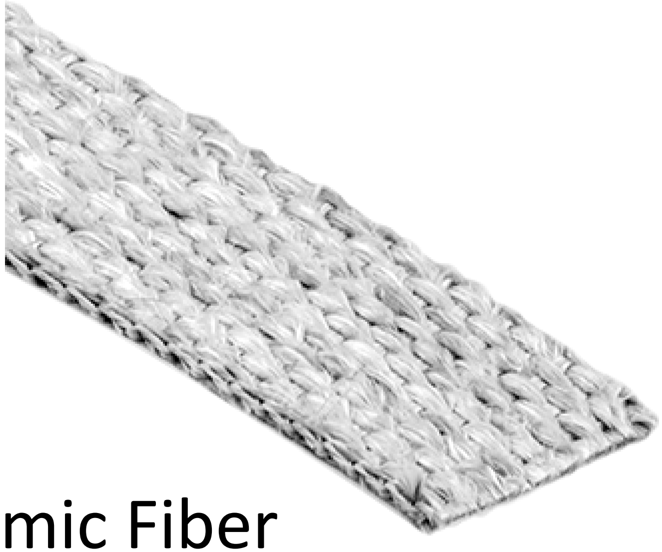
2in. Heating zone 10ft of wire

Applied Power: 12.9W



Thermal Insulation – Ceramic Fiber

Requirement 4.1
"The storage material must be heated to 300 degrees Celsius and not exceed 350 degrees Celsius."



Material: Calcium Aluminum Silicate Ceramic Fiber

Temperature Rating: -40°C to 800°C

Heat Flow: .82 Btu @ 426°F

Heat Loss & Required Power

Energy Required, 10ft. of wire @ 300°C: 12.9W

350°C: 15.42W

$$\text{Adiabatic fin tip: } \dot{Q}_{\text{adiabatic tip}} = -kA_c \left.\frac{dT}{dx}\right|_{x=0} = \sqrt{hpkA_c}\,(T_b - T_\infty)\tanh mL \qquad (3\text{–}65)$$

Requirement 4.1

"The storage material must be heated to 300 degrees Celsius and not exceed 350 degrees Celsius."

300°C Minimum

Voltage: **12.0V** Amperage: **1.075A**

350°C Maximum

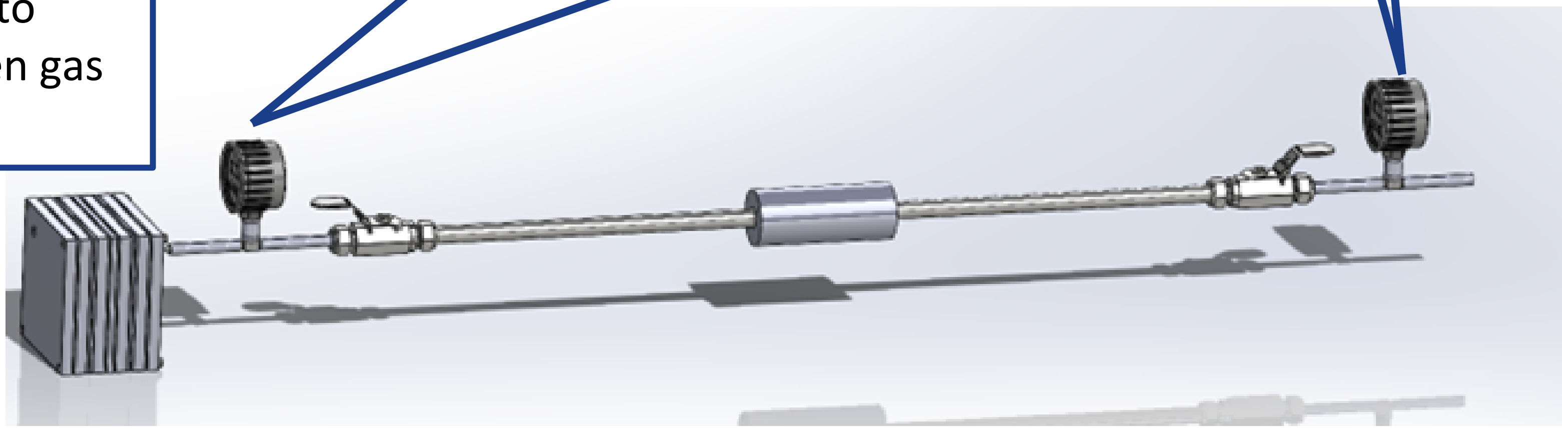
Voltage: **12.0V** Amperage: **1.285A**

User Interface (UI)

Pressure Gauges

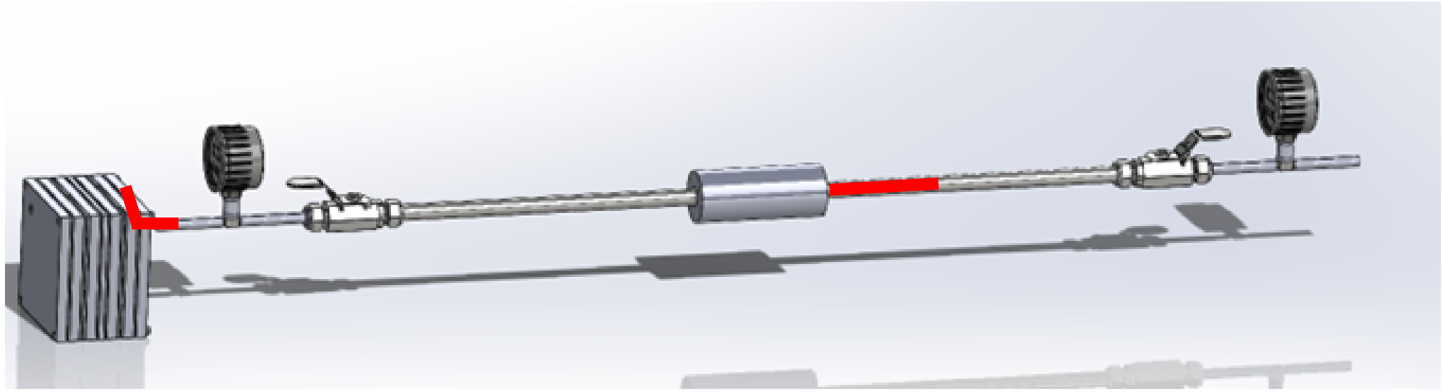
- 0-15 inWC (0-0.541 psi)
- ±2-1-2% accuracy
  - 0-3.75 inWC: ±0.3 inWC
  - 3.75-11.25 inWC: ±0.15 inWC
  - 11.25-3.75 inWC: ±0.3 inWC

Requirement 1.1.2
"The system must be able to determine the rate of hydrogen gas produced."



Thermocouples

- 2 thermocouples
- Integrated at Electrolysis and PTFE interface
- Integrated under Insulation in heat zone (high temperature insulated probe)



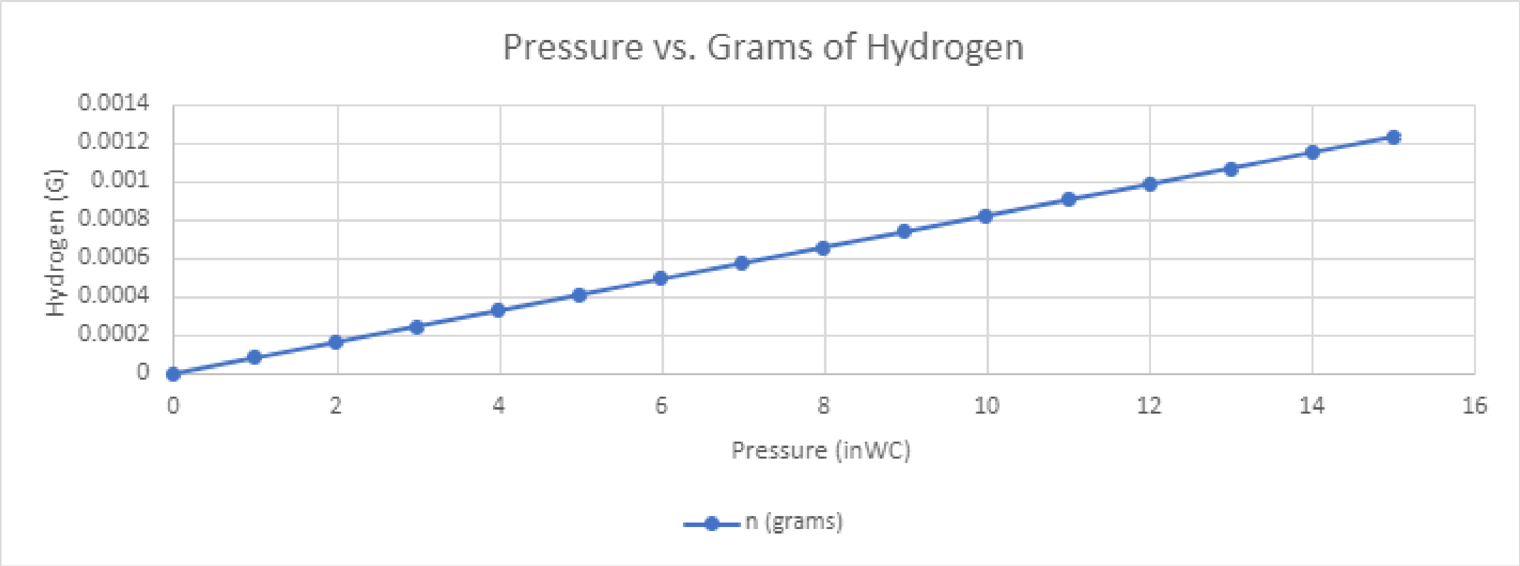
Governing Equations

$$PV = mRT$$

Where:

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

Requirement 1.1.2
"The system must be able to determine the rate of hydrogen gas produced."



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Mass Measurement

Chemistry lab scale to measure storage system mass

±0.0001 accuracy, 220 g Max

Storage capsule is about 20 grams

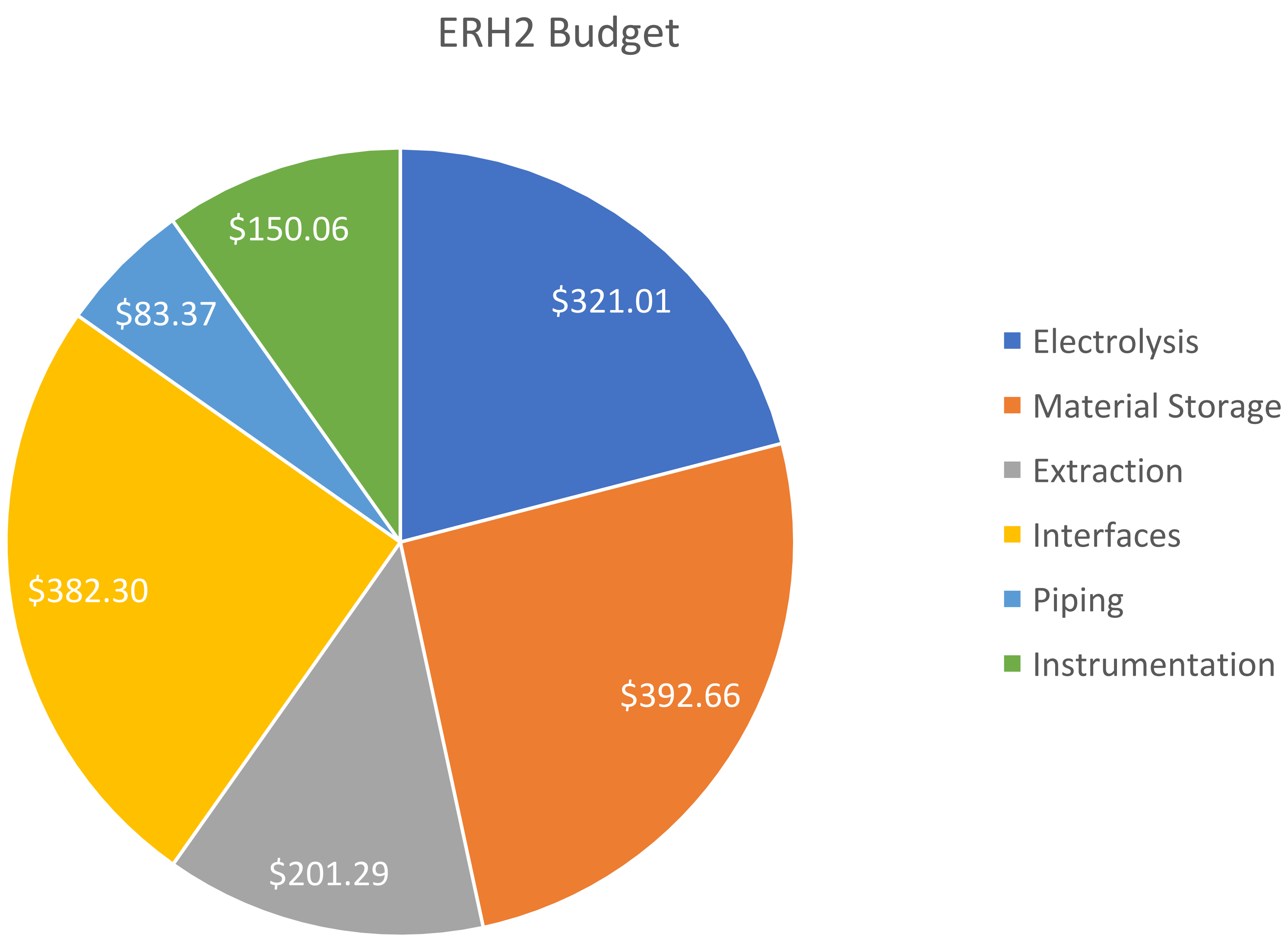
Requirement 1.2.1

“The system must measure the amount of hydrogen stored.”

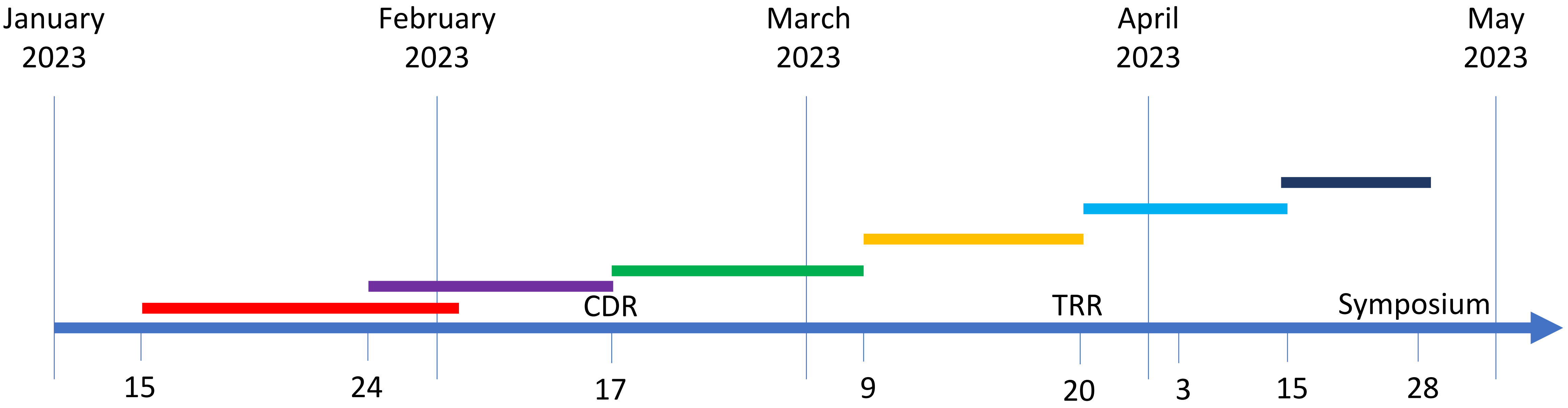
Budget and Schedule

Budget

- Total: $1530.69
- $230.69 over budget



Schedule



- Delta PDR prep
- Drawings and CDR prep
- Procurement and Fabrication
- Test Plans and TRR prep
- Testing
- Final Report

ERH2

References

- [1] A. Murali, M. Sakar, S. Priya, R. J. Bensingh, and M. A. Kader, “Graphitic-Carbon Nitride for Hydrogen Storage,” in Nanoscale Graphitic Carbon Nitride, Elsevier, 2022, pp. 487–514. doi: 10.1016/B978-0-12-823034-3.00017-0.
- [2] “Fast leakage test,” *Unitem Wrocław*, 28-Apr-2022. [Online]. Available: https://unitemmachines.com/our-offer/fast-leakage-test/. [Accessed: 08-Dec-2022].
- [3] “Remington Industries.” [Online]. Available: https://www.remingtonindustries.com/
- [4] “McMaster-Carr.” [Online]. Available: https://www.mcmaster.com/
- [5] https://www.scielo.br/j/qn/a/KyQvF9DMHK6ZJXyL5zQNy7N/?lang=en&format=pdf
- [6] https://www.gichemicals.ie/Potassium-hydroxide.html#:~:text=Potassium%20Hydroxide%20is%20manufactured%20using,concentrated%20to%2050%25%20using%20evaporation.

Questions?

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Additional Slides

- Requirements
- Generation
  - Natural Gas
  - Photobiological
  - Microbial Biomass conversion
- Storage
  - Physical
  - Material
- Equations
- Graphic Design
- Schedule
- Ideal Gas

Requirements Matrix

Requirements		Design Elements			
	Function 1.0	Electrolysis Device	Material-based Storage	Fuel Cell	Laws
	1.1	■			
	1.1.1	■			
	1.2		■		
	1.3	■			
	Safety 2.0				
	2.1	■	■		■
	2.2				■
	Education 3.0				
	3.1	■	■	■	
	3.1.1	■	■		
	3.1.2.1	■			
	3.1.2.2		■		
	3.1.3	■	■	■	
	3.1.4	■	■	■	
	Performance 4.0				
	4.1	■			
	4.1.1	■			
	4.2				■
	4.2.1	■	■	■	
	4.3	■			
	Human Factor 5.0				
	5.1				■
	5.2				■

Generation - Natural Gas

Methane Resource

- Methane is collected from a source (usually from natural gas)

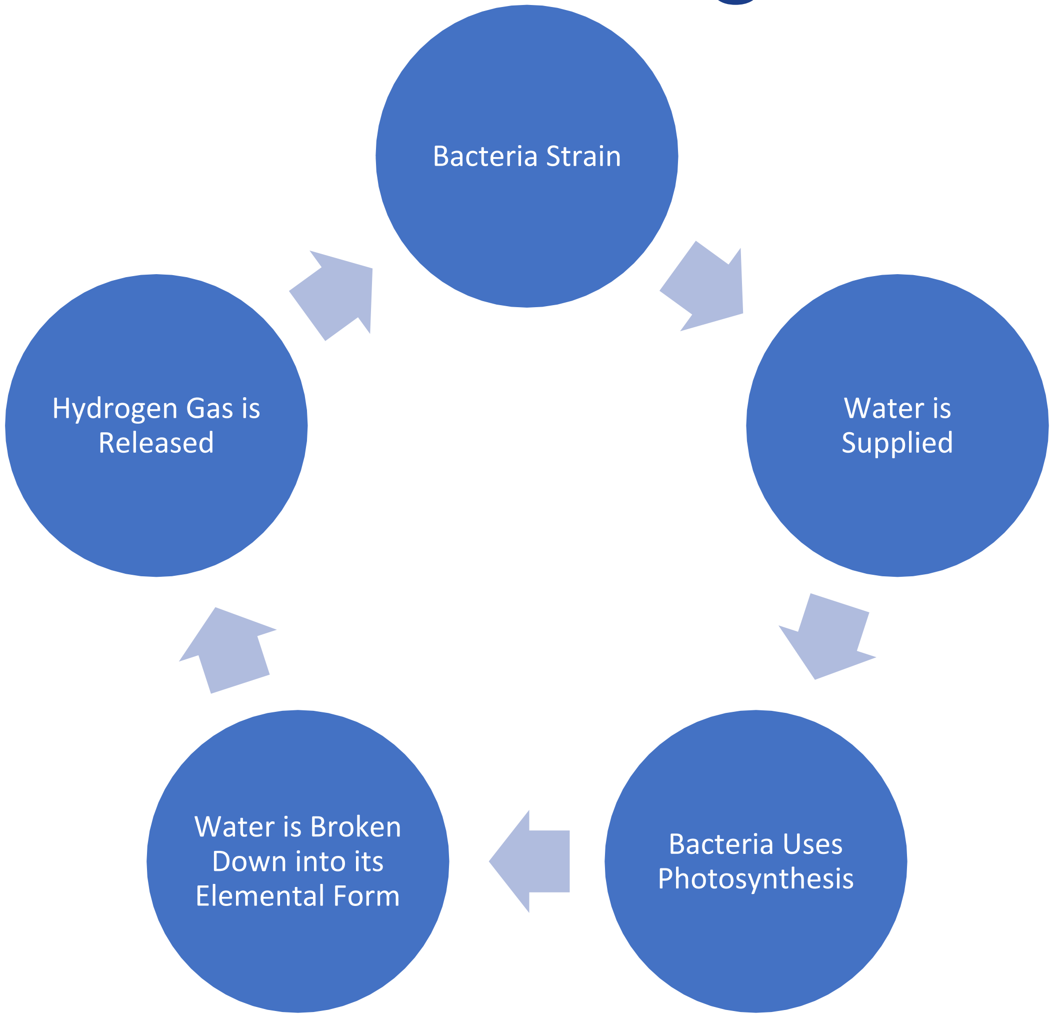
Steam-Methane Reforming

- High temperature steam (at 700-1,000 °C) is added to the methane gas

Hydrogen Extraction

- Hydrogen gas is extracted from the steam-methane mix from an added catalyst

Generation - Photobiological



Generation - Microbial Biomass Conversion

Storage – Physical Storage

Compressed

5,000-10,000 PSI

Unique Pressure Vessels

Cryogenic

Liquid H_2 at -252.2 °C

Solid H_2 at -259.14°C

Storage – Material Storage

Adsorbtion

Hydrogen is Stuck to the Compound's Surface

Absorption

Hydrogen is Encased by the Compound

Equations – Area of Mesh

$$64\ (in^2) * 0.66 = 42.24\ (in^2)$$

Equations – Max Current

$$\frac{0.084\ (A)}{1\ (cm^2)} * \frac{1\ (cm^2)}{0.155\ (in^2)} * 42.24\ (in^2) = 22.89\ (A)$$

Equations – Rate of O2 Production

$$\frac{22.89\ (C)}{1\ (s)} * \frac{600\ (s)}{96{,}485\ (C)} * \frac{1\ (mol\ O_2)}{4\ (mol\ e^-)} * \frac{31.998\ (g\ O_2)}{1\ (mol\ O_2)}$$

$$= 1.139\ (g\ O_2)$$

ERH2

Schedule of Project

- [Date tracking Gantt ERH2 (version 1).xlsb.xlsx]

Milestone description	Assigned to	Progress	Start	Days
Request for Proposals				
Requirements		100%	8/29/2022	4
Deadlines		100%	8/29/2022	3
Budget		100%	8/29/2022	2
Schedule		100%	8/29/2022	1
Design Concept Review				
Draft		100%	9/20/2022	15
Slide Design Review		100%	10/3/2022	9
Design Concept Proposal				
Front Matter		100%	9/12/2022	10
Similar Systems		100%	9/12/2022	10
Potential Risks		100%	9/12/2022	10
System Concept		100%	9/9/2022	19
Trade Studies		100%	9/20/2022	6
Budget		100%	9/19/2022	7
Energyland Layout		100%	9/27/2022	4
Conclusions		100%	9/12/2022	14
Draft		100%	9/9/2022	26
System Drawings		100%	9/20/2022	6
Schedule		100%	9/12/2022	13
Preliminary Design Review				

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Misc. Interfacing Table

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

Ideal Gas Law

$PV = nRT$

Where:

P = Absolute pressure of the gas (KPa)
V = Volume of the gas (L)
n = Amount of the gas (g)
R = Ideal gas constant (KJ/Kg*K)
T = Absolute temperature of the gas (K)

Calculations

Heat Loss / Required Power

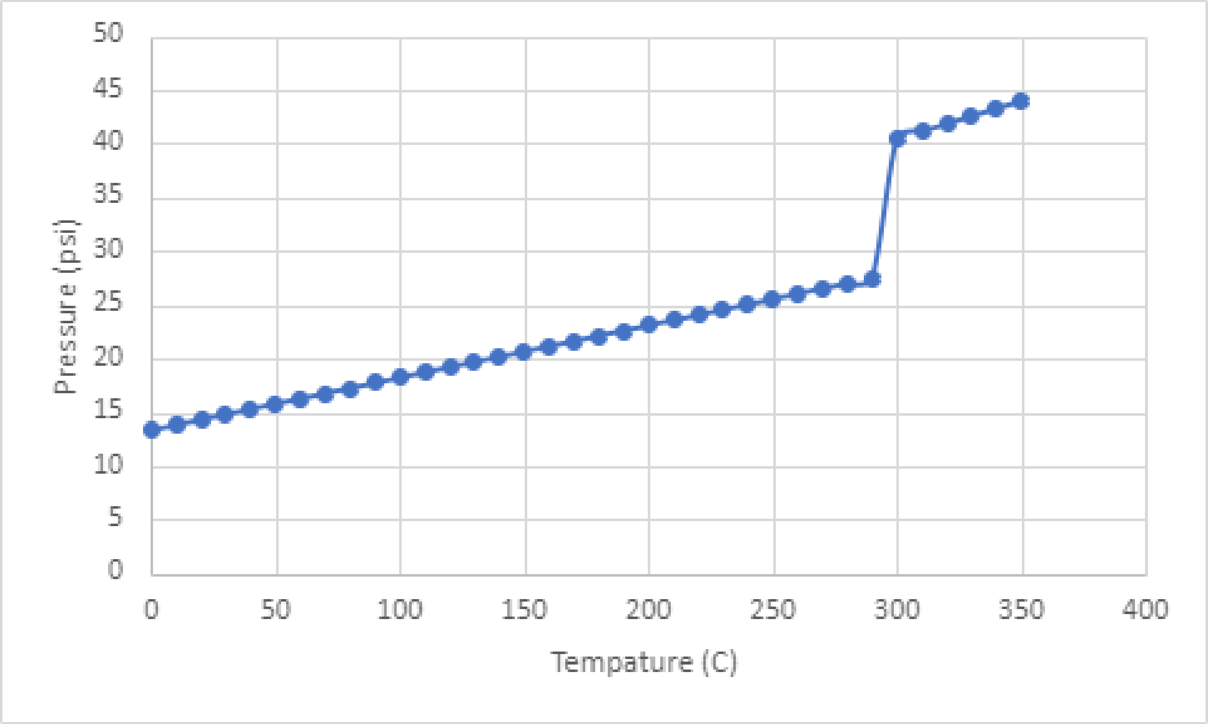
Outer Diameter:	0.75	0.75	(in)
Inner Diameter:	0.68	0.68	(in)
Thermal Conductivity	20	20	(W/m*K)
Surface Temperature	350	50	(°C)
Outer Diameter	0.01905	0.01905	(m)
Gravitational Constant	9.81	9.81	(m/s^2)
Bulk Temperature	20	20	(°C)
Volume Expansion Coefficie	2.18E-03	3.27E-03	(K^-1)
Kinematic Viscosity	3.26E-05	1.66E-05	(m^2/s)
Grashof Number	4.59E+04	2.43E+04	
Prandtl	0.69884	0.7268	
Rayleigh	3.21E+04	1.76E+04	
*Rayleigh < 10^12, we can use the book's equation!			
Nusselt Number	5.80E+00	5.03E+00	
Thermal Conductivity	0.036726	0.02625	(W/m*K)
Convection Coefficient	1.12E+01	6.93E+00	(W/m^2*K)
Inner Diameter	0.017272	(m)	
Perimeter	0.05984734	(m)	
Cross-sectional Area	5.07214E-05	(m^2)	
Thermal Conductivity	381.62	395.5433071	(W/m*K)
x	11		
Convection Coefficient, Avg	9.06E+00	(W/m^2*K)	
Thermal Conductivity, Avg	20	(W/m*K)	
m	2.31E+01		
cosh^-1(x)	3.088969905		
Length	1.34E-01	(m)	
Qdot through Fin	7.71E+00	(W)	

Outer Diameter:	0.75	0.75	(in)
Inner Diameter:	0.68	0.68	(in)
Thermal Conductivity	20	20	(W/m*K)
Surface Temperature	300	50	(°C)
Outer Diameter	0.01905	0.01905	(m)
Gravitational Constant	9.81	9.81	(m/s^2)
Bulk Temperature	20	20	(°C)
Volume Expansion Coefficient	2.18E-03	3.27E-03	(K^-1)
Kinematic Viscosity	3.26E-05	1.66E-05	(m^2/s)
Grashof Number	3.89E+04	2.43E+04	
Prandtl	0.69884	0.7268	
Rayleigh	2.72E+04	1.76E+04	
*Rayleigh < 10^12, we can use the book's equation!			
Nusselt Number	5.57E+00	5.03E+00	
Thermal Conductivity	0.036726	0.02625	(W/m*K)
Convection Coefficient	1.07E+01	6.93E+00	(W/m^2*K)
Inner Diameter	0.017272	(m)	
Perimeter	0.05984734	(m)	
Cross-sectional Area	5.07214E-05	(m^2)	
Thermal Conductivity	381.62	395.5433071	(W/m*K)
x	9.333333333		
Convection Coefficient, Avg	8.83E+00	(W/m^2*K)	
Thermal Conductivity, Avg	20	(W/m*K)	
m	2.28E+01		
cosh^-1(x)	2.92385707		
Length	1.28E-01	(m)	
Qdot through Fin	6.45E+00	(W)	

ERH2

Vessel Pressure

- Maximum Vessel Pressure: 40.43psia
  - Champagne Bottle: 90psia
  - Soda Can: 30psia



ERH2

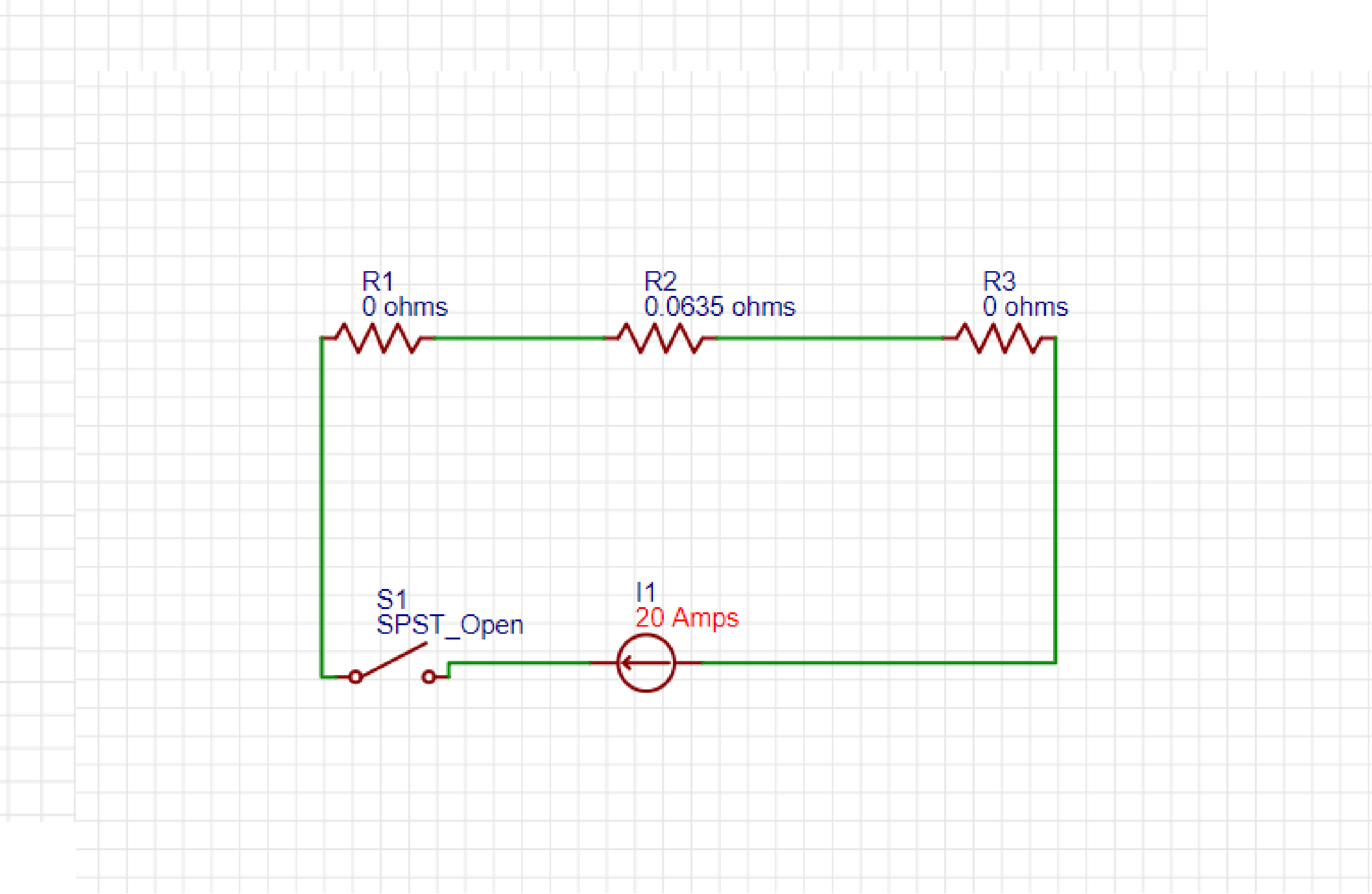
Electrolysis Power Circuit

R1 = R3

- Nickel Mesh

R2

- Salt Water



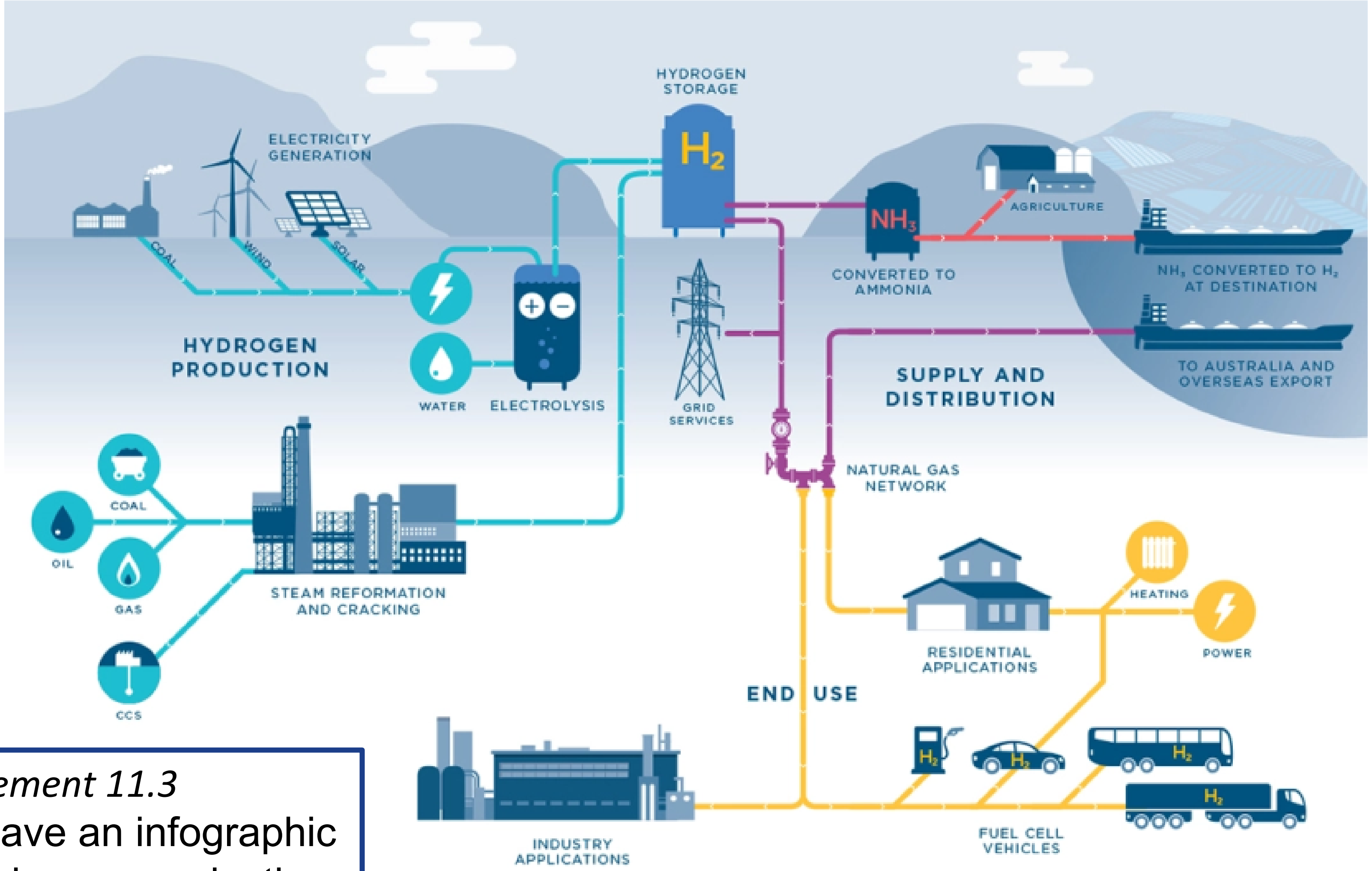
ERH$_2$

Risk Matrix – Before Mitigation

Asset or Operation at Risk	Hazard	Scenario	Opportunities for Prevention or Mitigation	Probability	Overall Hazard Rating
Overall System	Explosion	Hydrogen Leak, normal operation	Sealant	Seldom	2B
Electrolysis	Electrocution	Short Circuit	Insulator	Seldom	2C
Electrolysis	Fire	Excess Oxygen	Planned Dispersion	Seldom	2B
Electrolysis	Ozone	Ozone production	Capture	Improbable	1C
Heating Element	Burns	Contact with Heating Element	Warning Sign	Occasional	3C

Risk Probability	Risk Severity				
	Catastrophic A	Critical B	Moderate C	Minor D	Negligible E
5 – Frequent	5A	5B	5C	5D	5E
4 – Likely	4A	4B	4C	4D	4E
3 - Occasional	3A	3B	3C	3D	3E
2 – Seldom	2A	2B	2C	2D	2E
1 – Improbable	1A	1B	1C	1D	1E

Infographic



Requirement 11.3
"The IUI must have an infographic detailing the hydrogen production methods, storage methods, and uses."

[Hydrogen Economy Infographic – Herbert Smith Freehills]