Process Hazard Analysis of Alternate Hydrogen Production Methods

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by

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COLLEGE OF ENGINEERING

DECLARATION

I hereby declare that the project report titled '**Process Hazard Analysis of Alternate Hydrogen Production Methods**' submitted by Leon John DAlmeida, for the award of the degree of *Professional Master's Program in Chemical Engineering* to Purdue University, is a record of work carried out by me under the supervision of academic mentors (Dr. Ray Mentzer & Dr. William R. Clark) and industrial mentors (Mr. Edward Marszal, Mr. David Moore & Mrs. Rebecca Peterson).

Further, I declare that the work reported in this project report has not been submitted and will not be submitted, either partially or in full, for the award of any other degree or diploma in this institute or any other institute or university.

Signature of candidate

Place : West Lafayette

Date : 07/31/2023

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ACKNOWLEDGMENT

"Success is often the result of taking a wrong step in the right direction"

I owe my profound gratitude to the academic and industrial mentors for their guidance throughout the project work and constant attention to excruciatingly tiny details and for inspiring ideas and criticism that have been remarkably valuable in the entire process.

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Abbreviations

BoP	Balance of Plant
CAGR	Compound Annual Growth Rate
CL	Concentration Layer
CSB	Central Board of Investigations
ESTA	Employee Safety Training Assessment
FMEA	Failure Mode and Effects Analysis
GDL	Gas Diffusion Layer
HAZID	Hazard Identification
HAZOP	Hazard & Operability Study
HER	Hydrogen Evolution Reaction
HT-PEMFC	High Temperature Proton Exchange Membrane Fuel Cell
LT-PEMFC	Low Temperature Proton Exchange Membrane Fuel Cell
MEA	Membrane Electrode Assembly
OER	Oxygen Evolution Layer
OSHA	Occupational Safety and Health Administration
P & ID	Piping & Instrumentation Diagram
PAFC	Phosphoric Acid Fuel Cells
PBI	Polybenzimidazole
PEM	Proton Exchange Membrane
PFD	Process Flow Diagram
PFSA	Perfluorosulfonic acid
PHA	Process Hazard Assessment
PI	Polyimides
PPE	Personal Protective Equipment
QRA	Qualitative Risk Assessment
SCSRs	Self-Contained Self-Rescuers
SOEC	Solid Oxide Electrolytic Cell
SOP	Standard Operating Procedure
SPE	Solid Polymer Electrolyte
SPEEK	Sulfonated Polyether Ether Ketone
WHA	Workplace Hazard Assessment

Literature Review

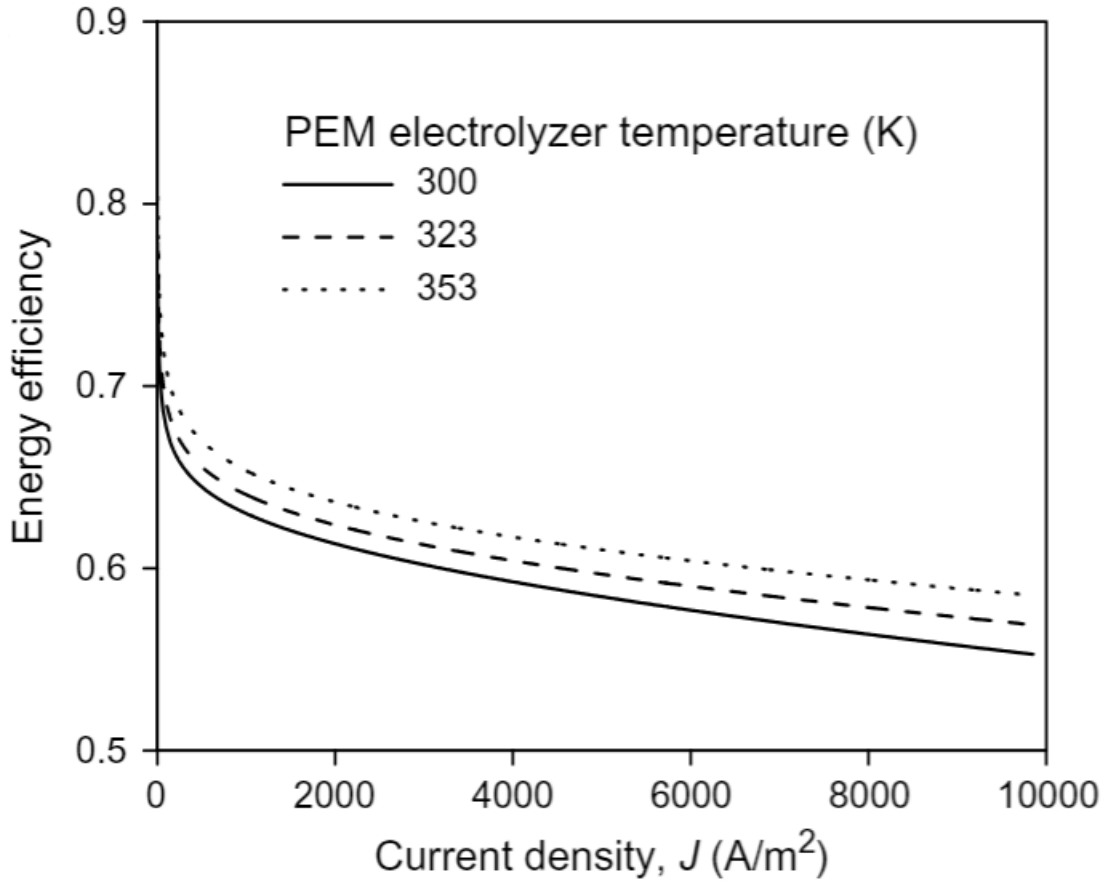
At present, majority of global hydrogen production (96%) comes from fossil fuels, whereas only 4% is produced through water electrolysis. Fossil fuel-based hydrogen production results in lower purity and higher greenhouse gas emissions. In order to address the depletion of fossil fuels and the environmental impact of hydrogen production, water electrolysis powered by renewable energy sources is considered a promising alternative. This research project focuses on Proton Exchange Membrane (PEM). PEM electrolyzers offer advantages like high current density, compactness, and fast response. PEM & SOEC have been introduced to generate H_2 energy. PEM is currently available for production, whereas SOEC is still undergoing research. Generally specifications for each electrolyzer model are provided by the manufacturers and vendors as per their requirements. Water electrolysis cannot be exploited for hydrogen production, as a part of it is lost due to "heat". In order to overcome the issues faced by Alkaline electrolyzer, PEM electrolyzer has been developed. Due to the expensive catalyst materials like platinum, rhodium and other precious metals used in their production, reducing the cost while maintaining high efficiency is a significant challenge for all electrolyzers [1]. High production cost raises its market value and results in slow development. Investigations have been carried out by researchers to understand the relationship of current ripple formation between thristor-based and classic chopper rectifiers and have reached a conclusion that the current ripple need to be as small as possible in order to optimize energy consumption. Analysis was performed on the large rectifiers on the impedance vs frequency to evaluate the challenges faced, such as power quality and control. In order to improve the Hydrogen flow rate, it is vital to control the current passing through the rectifier [2]. Water electrolysis provides an effective alternative fuel to cope with the decline in fossil fuels. Electricity generated via power grid is not an ideal source to supply electrolyzers, since most of the electricity is generated by fossil-fueled power plants (i.e., coal and natural gas-fired power station) results in greenhouse gas emissions (e.g. CO_2, CO).

Energy storage (such as Hydrogen buffer storage) helps to regulate consumption and production. Based on PEM stack electrical needs, energy can be supplied to the PEM electrolyzers via variety of AC-DC converters. The stack voltage, which ranges from few to hundreds of volts, depends heavily on the rated power of the device, where current varies between rates of ten to

thousands of amps (Or, in the watt to megawatt range). Different requirements and specifications must be considered prior to selecting a suitable AC-DC converter for Electrolyzer application [4]. To avoid cases of power switch failures and current ripple reduction, design of the step-down DC-DC converter is recommended. In order to enhance power quality, we can combine rectifier and DC chopper to avoid the use of bulky active and passive filters. It is anticipated that the use of hydrogen technologies will also expand into other industries, such as transportation, mobility, electrical micro-grids, and even residential applications. In order to do so, efforts must be intensified on enhancing characteristics of hydrogen-based systems, such as effectiveness, start-up speed, etc. The advancement in Hydrogen technology focuses on improving existing electrolyzers, making it more effective, lightweight, and long-lasting. For this reason, research is currently being done on improving the stack technology (which is primarily based on Proton Exchange Membrane), whose size depends on the electrolyzer's power, that improves performance of the stack [5]. One of the many solutions is to combine the renewable energies (e.g wind, solar etc.) so that it can meet the entire energy requirements of the world, as the single source of renewable energy is not sufficient to meet the growing demand [6].

The colour spectrum of the hydrogen can change over time with advancement in technology [8]. Most investigations on PEM electrolysis focus on improving catalysts and PEM electrolytes. However, current research and literature lacks detailed thermodynamic and electrochemical modeling analyses on PEM electrolytic hydrogen production, which is essential for better understanding of its working mechanisms and design optimization [7]. From Fig. 1, we can deduce an inverse relationship between energy efficiency and membrane thickness. Thicker electrolyte membrane has higher ohmic over-potential, and higher operating potential, that result in lower energy efficiency.

Fig 1. PEM Electrolyte Thickness vs Energy Efficiency



Hydrogen has so far been handled safely for many years and used in a number of applications, including but not limited to aerospace technology, chemical processing, food, and electronics industries. In the past, safety precautions for using the earliest forms of energy (such as wood) were created through trial and error [9]. The new energy systems should include safety planning as a fundamental component of its design and operation that includes identifying hazards, assessing risks by taking into account the likelihoods and ramifications of incidents related to those hazards, and minimizing risks. At present PEM electrolyzers are the most common type of units that are used in commercial settings. The focus of this study will be on hazard and risk analysis in order to determine level of risk and need for safeguard in hydrogen generation systems. Hazard and Operability (HAZOP) study is the particular Process Hazard Analysis (PHA) technique used for hazard and risk analysis in the hydrogen generation system. Prior to conducting a HAZOP study, a failure analysis is created in order to identify possible failures to

set up process deviation. The fundamental idea behind a HAZOP study is to thoroughly describe the process and create a (Process Hazard Analysis) PHA on the basis of consequence indexed to determine what the causes and effects of these deviations may be [10]. Numerous studies on the various risks associated with H_2 use have been carried out, with a focus on hydrogen fueling stations, unintended release of H_2 and H_2 jet flames; that helped in carefully building systems for analysis based on the prototype system [22]. It has been observed by several researchers that if electro-osmotic drag prevails over back diffusion, the anode will dry out while cathode will remain hydrated at high current densities, whereas it is opposite at low current densities since Hydrogen gas will diffuse back to the anode causing an explosive reaction [24].

Introduction

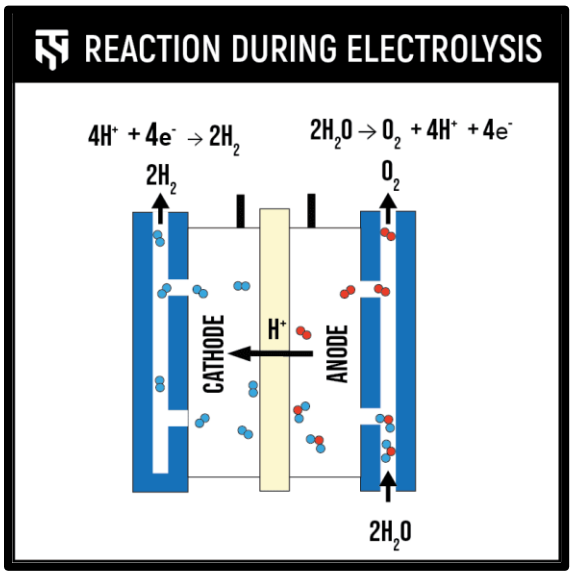
The main focus of this project is to develop a series of hazardous scenarios that should be considered when implementing PEM that includes a discussion of causes, consequences, and typical safeguards. This information was developed and presented through the technique and documentation style of HAZOP.

Hydrogen: Hydrogen is considered as an efficient fuel. Since it is chemically bonding with most of the elements, it has been used as an industrial chemical for many years. Hydrogen is used in automobiles to combine with Oxygen in fuel cells to produce electricity and to power the engine [11]. Though Hydrogen can be produced in different forms, this project will focus only on electrolysis process. Since it is not freely available in nature it is produced from other alternative sources of energy [13]. Unlike carbon-based fuels, hydrogen produces no harmful by-products when burned. The combination of hydrogen and oxygen in fuel cells only produces electricity, heat and clean water [11].

Electrolysis: Hydrogen exists in gaseous form at standard temperature and pressure (273K and 1013 hPa) and is available in the atmosphere at 29.534 vol% as an element. Electrolysis is one of the methods to extract hydrogen from water by using electricity. It produces carbon free hydrogen from nuclear and renewable sources. PEM technology efficiency ranges from 50% to 80% [16]. This reaction takes place in a device called an electrolytic cell. Electrolyzers size ranges from small unit-size and are suitable for small-scale decentralized hydrogen production to large centralized manufacturing plants that can be directly connected to greenhouse gas-free renewable and other forms of power generation. Similar to a fuel cell, electrolyzers consists of a membrane that separates the anode and cathode from mixing. Due to differences in the types of electrolyte materials that they contain and the ionic species they conduct, electrolyzers operate in different ways [13]. During two partial reactions cracking occurs at the two electrodes of the electrolytic cell; the cathode (-) and the anode (+). In practice, electrolytic devices consist of several interconnected electrolytic cells, also called stacks. When the voltage is switched on, electrolysis reaction takes place. Between the two partial reactions, charge equalization occurs in the form of conduction of the ion through the electrolyte. In addition, a membrane is required

to separate the two reactions and prevent product gases from mixing or reacting. The type of electrolyte and the ionic charge differ in different electrolysis techniques [19].

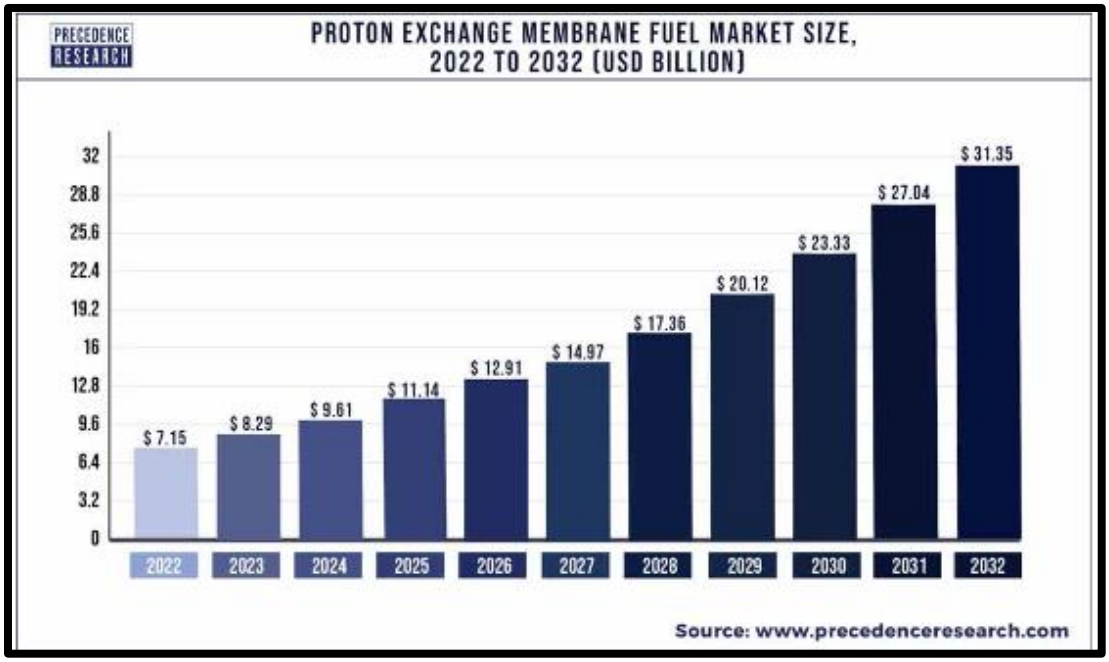
Fig 2. Electrolysis Process in PEM



Market: Proton Exchange membrane Market size was valued at around USD 8.29 billion in 2023 and is expected to reach a value of approximate USD 32 billion by 2032, at a CAGR (Compound Annual Growth Rate) of 17% over the forecast period of 2023 to 2030 as referred in fig 3. This indicates a positive outlook for the market, driven by increasing demand for clean energy solutions and advancements in fuel cell technology. The main drive is the growing demand for electric vehicles. PEM market provides several opportunities for expansion in the coming years. It is one of the key opportunities in the development of new materials and manufacturing process that can reduce costs and improve the performance of the fuel cell. In terms of revenue, automotive held the largest market share of 29% [19]. It is anticipated that the growing popularity of medium, commercial, light, and heavy-duty cars will increase demand for PEM fuel cell. Due to its high power density and capability to operate in chilly conditions it enables a wide range of stationary applications. In 2022, the high temperature market segment had the largest market share recorded. The utility of High-Temperature Proton Exchange Membrane Fuel Cells (HT-PEMFC) in terms of system requirement changes constantly and is typically operated in hybrid mode alongside a battery. Buildings that use combined heat and power can benefit from the HT-PEMFC systems that runs on natural gas which requires a

suitable controller and system for operating in a desirable situation. HT-PEMFC can operate at temperatures ranging from 120°C to 200°C. The Low-Temperature Proton Exchange Membrane Fuel Cell (LT-PEMFC) can operate at temperatures ranging from 60°C to 80°C. Perfluorosulfonic acid (also known as Nafion) is typically used as the membrane in LT-PEMFCs. The LT-PEMFC operates at temperatures lower than 100°C because Nafion is sensitive to change in its internal moisture level [20].

Fig 3. Proton Exchange Membrane Global Market Growth (2023-2032)

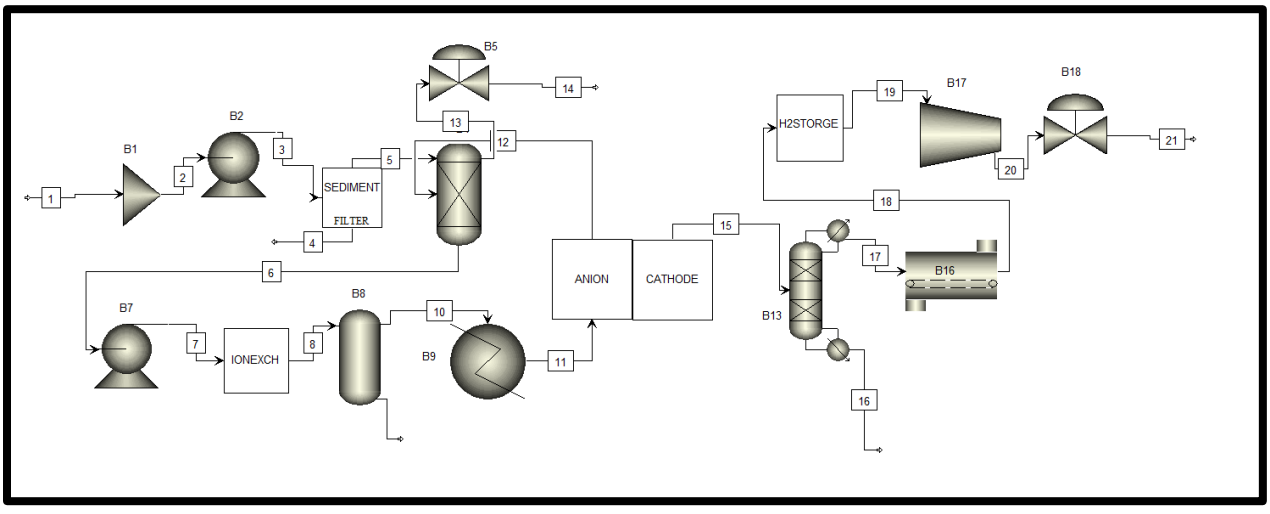


Process

The pretreated feed is first sent to the mixer. Since water may contain suspended particles, it needs to be mixed well before sending it to the sediment filter for filtration. Hence the main purpose of the mixer is to ensure efficiency of the sediment filter by preventing any coagulation of the sediments. The pretreated feed is pumped to the filter and main purpose of the pump is to maintain a steady and consistent flow, allowing the filter to capture and remove larger particles before sending the water to the separator. The pretreated feed is then sent to the sediment filter for filtration and extraction of any solids (sediments). After the filtration process the treated water is sent to the H_2O-O_2 separator for removal of O_2 to which the O_2 is vented out and water

is drained downstream. Hydrogen and Oxygen are highly flammable gases, and the main purpose is to keep them separated to reduce the risk of any potential fire/explosions. The water is then pumped to the ion exchanger to remove ions as water accumulation in the membrane can cause scaling or fouling on the surface of the PEM over time, by removing these ions we can extend the membrane life. The water is then heated by an electric heater inserted into the main water tank to ensure the proper process temperature during stack operations. By electrolysis process H_2 is obtained at the cathode and the mixed stream (O_2-H_20) is obtained at the anode. Assuming the process is not a full 100% conversion, the mixed stream is vented back to the separator and H_2 is sent to the extractor for drying or removal of moisture. After extracting the moisture from the product stream, it is sent to a 2-bed dryer for absorption and regeneration from which water is drained out. Once the moisture is completely drained out from the product stream it is then sent to the buffer storage to maintain the balance between consumption and production. The product stream is then pumped out to the gas export pipeline under high pressure. If there is still moisture content in the product stream then it is sent back to the extractor to repeat the same process to prevent any explosive reaction in the buffer storage. Meanwhile the dryer can act as a regenerator to generate the H_2 gas and send it to the buffer storage. The main purpose why moisture content should be removed is to prevent any corrosion, maintain the storage structural integrity, as there will be a risk in pressure fluctuations due to the temperature changes and could cause unwanted reactions and result in releasing the undesirable byproducts [14].

Fig 4. Archetype Process Flow Diagram For H2 Production Using Proton Exchange Membrane



Proton Exchange Membrane (PEM): The "Membrane Electrode Assembly (MEA)" is an important part of the PEM that includes the membrane, the catalyst layers, and the gas diffusion layer (GDL). The electrolyte can either be fluorinated, sulfonic acid or polymer membrane. Water is electrolyzed using a Proton Exchange Membrane (PEM) in a cell with a Solid Polymer Electrolyte (SPE) that separates the product gases, conducts protons, and insulates the electrodes from electricity. In terms of power supply, a commercial AC/DC converter will supply power to the electrolyzer from the electrical power grid to which a commercial DC/DC step-down converter is inserted to properly reduce the stack voltage as hydrogen flow is proportional to the electrical current supplied. This converter enables continuous voltage output regulation over a sufficiently wide range. The ability of PEM electrolysis to function at high current densities is one of its biggest advantages. At times energy is uncaptured due to sudden spike in the energy input, especially for high dynamic energy sources such as wind and solar and can operate at high current densities lowering the operation cost [16]. PEMs are frequently used to produce hydrogen and generate electricity hence it is a dual function provider. Due to high ionic conductivity and good mechanical strength membranes like Nafion and Nafion-based are used but has its drawbacks such as lengthy synthesis process and poor proton conductivity at high temperatures. PEM electrolyzers have advantages of being able to operate at high voltage and current densities while producing hydrogen gas that is up to 99.995% pure. The Oxygen Evolution Reaction (OER) begins when hydrogen ions move from the anode to the cathode through the PEM as a result of electrolysis. When hydrogen ions are reduced at the cathode, one hydrogen (H_2) molecule is released, and this initiates the Hydrogen Evolution Reaction (HER) as shown in fig 5. [18].

Fig 5. Overall Electrolysis Reaction

Reactions	
Anode	$H_2O \rightarrow 2H^+ + ½\ O_2 + 2e^-$
Cathode	$2H+ + 2e^- \rightarrow H_2$
Overall	$2H_2O \rightarrow H_2 + ½\ O_2$

Parameters Affecting the Membrane-Based Electrolysis: The first parameter to be considered is the “operating temperature” in which a typical Nafion-based membrane serves as the main element of the membrane electrode in a PEM electrolysis process. This process can typically run at temperatures ranging from 31°C to 91°C approximately. Due to Nafion membrane's inability to withstand operating temperatures above the specified range, it results in mechanical degradation and a loss of ionic conductivity, because the electrochemical reaction has faster kinetics at higher operating temperatures. The second parameter is the “concentration” in which the amount of hydrogen produced and the rate of the reaction, that are strongly influenced by electrolyte concentration. A greater concentration in the electrolyte boosts the solution's ionic conductivity, which encourages hydrogen evolution reactions and boosts yield. The membrane, electrodes, gasket, current collector, bipolar plates, and other parts of the MEA can deteriorate due to an excessive electrolyte concentration, which in turn affects the hydrogen yield. Concentrated electrolytes, whether acidic or alkaline, have corrosive properties that can harm the pump, the tubes, thermocouples and other heating elements [18].

One of the variables that can affect the kinetics of the electrolyte is the flowrate in the electrolysis reaction because the membrane functions as the electrolyzer's central component. The electrolyzer has improved in many areas over past ten years, but the effects of different operating parameters are still being studied. Notably, kinetic and thermodynamic relationships have not yet been used to pinpoint the primary limiting factors. However, a faster electrolyte flowrate may act as a bottleneck, reducing the rate of ionization in a HER or OER instead of necessarily increasing the rate of hydrogen production. In order to achieve an optimal hydrogen yield, a good balance must be maintained between an optimal electrolyte flowrate and other parameters [18].

To achieve optimum performance it is necessary to hydrate the PEM. At times challenges can be faced such as the excess water in the stack either due to malfunction or rupture or more flow can fill the pores hindering the diffusion of Hydrogen to the cathode and decreases the efficiency of the catalyst, making it difficult to transport oxygen to the catalyst layer. The overall effect is referred to as 'GDL/CL flooding'. Oxygen mass transport is limited due to accumulation of water in the membrane. Whereas it has quite the opposite effect when the diffusion occurs

backwards, this can result in the drying phenomenon and poor performance. Another factor that can affect the performance of the membrane is due to the sharp increase in electrical resistance of the membrane which results in degradation of membrane life with increase in ohmic losses. Hence, a proper balance is maintained between water removal and production which is also necessary to maintain current densities. Drying condition are such that active sites on that catalyst are hindered by the sulfonic ion bonds increasing its activation polarization, in addition to degradation of the membrane (delamination). Therefore, maintaining high PEM water content is essential to ensure high ionic conductivity and also can use capillary transport to move water through the GDL [24].

Membranes

Nafion: Perfluorosulfonic acid (PFSA) membranes like Nafion are well-known and frequently used in PEM fuel cells and electrolyzers. Because of its excellent physicochemical qualities and good ionic conductivity, Nafion performs well and is currently favored. One of its main drawbacks is its high fuel permeability which causes "PEM fuel cell systems to lose a lot of fuel and perform less efficiently". Ion crossovers are another factor that lowers the hydrogen yield in PEM electrolyzers. Since membrane production cost is high, there have been multiple methods to address this shortcoming such as inorganic fillers, acid doping, and introduction of various polymer backbones into the Nafion membrane. More effective hydrogen synthesis can be achieved by running an electrolyzer cell at a higher temperature that results in the rise in ionic conductivity and decline in anode and cathode activation. At Higher temperatures PEM fuel cell performance is enhanced with increase in Hydrogen production at the expense of the fuel cell durability [18].

Polybenzimidazole (PBI): The term "Polybenzimidazole" (PBI) refers to the structure of aromatic heterocyclic polymers that contains multiple benzimidazole units. PBI membranes have a few advantages over Nafion membranes, such as better chemical stability, greater tensile strength and a specific affinity for "Polyaryletherketone" and a few other polymers. These qualities have led to extensive research into the use of "Polybenzimidazole-based (PBI-based)" membranes in fuel cells, water electrolysis, and flow batteries. Hybrid Membrane Synthesis is

one of the methods to help improve the PBI by focusing on the low conductivity to make it a good substitute. Combination with Sulfonated Polyether Ether Ketone (SPEEK), Sulfonated Polysulfone, or Sulfonated partially Fluorinated Arylene Polyether to create ion cross-linked structures are some of the notable examples [18].

Polyimide: Polyimides (PIs) are another group of promising polymers that are used for PEMs. PI's are aromatic and contain imide heterocyclic structure in the main backbone chain as depicted in Fig. 6. PI finds applications in many other fields owing to its superior thermal, mechanical and chemical stability at higher temperature in addition to its film forming ability. These characteristics are required for fuel cell membranes, therefore, with little modification, sulfonated PI's are abundantly used as PEMFCs [18].

Process Hazard Analysis

Balance of Plant: To cut costs and gain market share quickly, the developed system is made up of commercially available components that make up the Balance of Plant (BoP) around the electrolysis stack. BoP involves the following subsystems that are Heat Management Subsystems, Water Management Subsystems, Power Conditioning Subsystems and Control Subsystems [14].

Risk Analysis: By taking into account variables like likelihood and severity, risk assessment process aids in identifying hazards and quantifying the risks connected to those hazards. HAZOP, FMEA, HAZID, QRA, and other techniques are available for conducting risk assessments for specific systems to which the main focus will be on the HAZOP. Electrolyzers are subject to the same rules. Due to the presence of flammable gases, oxygen, electricity, high-pressure, high-temperature, and the potential release of gases beyond the recommended concentration, electrolyzers are considered as complex systems. If proper precautions are not taken, all these characteristics may result in fatal incidents [15].

HAZOP Study & FMEA (Failure Mode Analysis): One methodology that is frequently used by industries for assessing risk is conducting operability study (HAZOP). HAZOP offers a methodical way to assess the electrolyzer system's design and spot potential hazards that might have gone unnoticed during the general design stage. HAZOP is carried out following the first

design, that is, after the first P&ID (Piping and Instrumentation Diagram); the full system layout with all existing components is defined. Several sessions of HAZOP are held where a core team of individuals with the necessary skills come together to brainstorm. A HAZOP moderator with knowledge of the HAZOP method and a scribe who tracks progress should lead the sessions. Depending on the complexity, a system is divided into a number of nodes, and each node's hazards are identified using standardized guide terms and process parameters (consequences and causes) [15]. The analysis of the accident scenarios starts with investigating the parameters that result from the operation. FMEA is another brainstorming technique for identifying risks associated with the failure modes of system components. With both approaches, the effects and likelihood of accidents are qualitatively evaluated. Some of the derivation parameters in the HAZOP are temperature, pressure, voltage, and the chemical composition, more and less were used as indicators describing consequences and causes [22].

Nodes are integral part of the HAZOP and must be characterized to offer more understanding on the archetype PFD. The nodes are divided into four pathways in this process, node 1 which includes the pretreated feed all the way to the separator to separate water and Oxygen thus leading to the second node that is Oxygen vent. Node 3 is the water drained from the separator all the way to the PEM stack and finally node 4 is the electrolysis process to the H_2 gas export pipeline.

Definitions:

Hazard: Refers to a potentially harmful source. Deviations from the intended design or operation may be dangerous. HAZOP studies concentrate on hazards, and it should be noted that a single hazard may have the potential to cause various types of harm to the personnel and process safety. (Reference to the HAZOP worksheet).

Harm: Refers to physical harm or harm to people's health, environment, or property. The result of a hazard occurring is harm, which can take many different forms, including threats to user or patient safety, worker safety, business risks, regulatory risks, environmental threats, etc.

Risk: A combination of likelihood and severity. Since the core methodology does not call for the identification (also known as rating) of the probability or severity of harm, "risk" is not

always expressly identified in HAZOP studies. But if it's necessary, risk assessment teams may decide to rate these elements in order to more precisely quantify and rank risks.

Risk Severity Rankings: Using an ordinal scale is one of the most popular ways to describe risk severity. This is due to the fact that it is frequently challenging to precisely estimate the potential harm. A ranking system from least to most severe is known as an ordinal scale. The rating on the scale can be broken into the following: 1 = Negligible: The risk is so negligible that it can be disregarded by the team. 2 = Low: The risk is negligible and can be controlled by following standard procedures. 3 = Medium: The risk is significant, but it can be controlled or mitigated with additional measures. 4 = High: The risk is serious and demands immediate attention. 5 = Maximum: The risk is significant and requires attention. Depending on the viewpoint from which it is measured, the Risk Severity varies. The ordinal scale could be quantified using percentages, time, or cost overruns. This could lead to overlap. Risk Severity is influenced by a number of factors. For example, the size of the project may have an impact on the risk level. Project complexity can also influence the risk severity [23].

Explosion and Fire Safety: Combustible, oxidant, and ignition are the three elements needed for combustion, which are commonly represented by the fire triangle. All three of these substances can be found together in an Electrolyzer. Avoiding ignition sources is the most common practice. Due to hydrogen's low ignition energy, this is challenging. A hydrogen-air mixture can be ignited with just a static spark. In order to identify potential leak sources (during normal operation as well as failure modes), the system design should be reviewed by a team of experienced engineers as part of the assessment of explosion and fire safety. The failure modes and the internal characteristics of the systems are analyzed by FMEA and HAZOP [15].

Practices to Reduce the Risk of Explosion: The electrolysis course at WHA (Workplace Hazard Assessment) starts by looking into the possible electrolysis system failure modes. After that, it looks into various mitigation measures, such as: Prevent internal leakage from one area of the system to another and external leaks from combining hydrogen with outside air. Installation of mechanical ventilation fans will help to ventilate the electrolyzer enclosure and prevent hydrogen buildup. In order to properly vent O_2 and H_2 during system startup, operation, and shutdown, it is important to measure concentrations for all operational modes. Before and after

use, purge H_2 systems with nitrogen or other inert gases (optional). Use personal monitors, leak detectors, imaging cameras, and fixed H_2 gas detectors [21].

OSHA Regulations: (OSHA) Occupational Safety and Health Administration were created to ensure that safety protocols are setup to protect the workers and to provide different EPA level of protection, as listed in the table below [25].

Table 1: OSHA EPA Levels of Protection

Level	Type of Suit	Equipment	Protection Provided	Application	Limitation
A	Vapor Protective Suit	Chemical resistant gloves, chemical resistant boots, Two way radio communication	Skin, eye, respiratory	Chemical that has high level of hazards to respiratory, skin and eyes. Operations in poor ventilated areas	Integration without loss of performance must resist permeation.
B	Liquid Splash Protective Suit	Same as A	Same as A, less skin protection	Medium risk to skin, Hazards related to liquid contact.	Same as A
C	Support Function Protective Garment	Full Face piece, air purifying, canister equipped respirator	Same as B, less respiratory protection	Unknown Air contaminants, no affect to skin.	Same as B but airborne concentration must be less than IDLH levels, Atmosphere must contain at least 19.5% O2 concentration.
D	Coveralls, Safety boots, glasses or chemical splash goggles	Gloves, face shield	Minimal skin protection, no respiratory protection	No known hazards except for splashes, potential for inhalation or direct contact to chemicals.	Atmosphere must contain at least 19.5% O2 conc. , should not be worn in hot zones

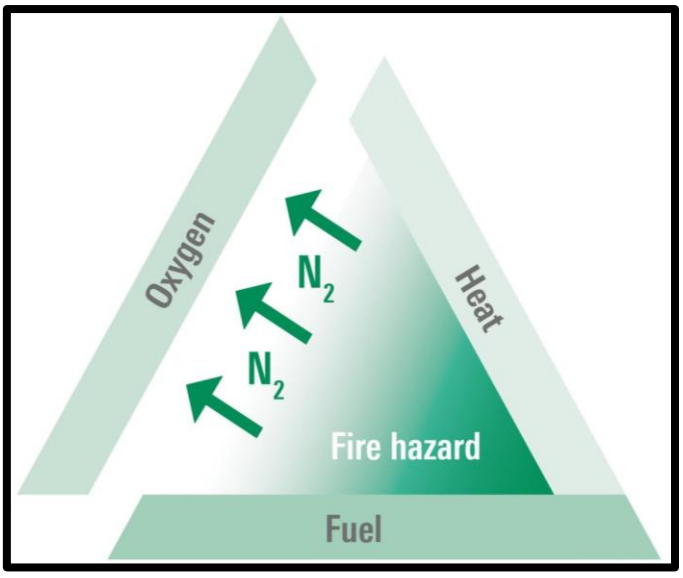
Workplace Hazard Assessment (WHA): It is essential to recognize that hazards are not necessarily present outside, but also inside the workplace. For this reason OSHA recommends that employers conduct inspection, testing and preventive measures all in the form of an 'SOP' and if hazards are identified 'PPE' and 'safety practices' need to be implemented. The next process will be to fill out a form to which "ESTA' will assign a particular training depending on the area and type of work the employee is carrying out [27].

Preventive Measures

Break the Fire Triangle: The main three components required to start the fire are: oxygen, heat energy or fuel which are dependent on each other. Flammability of the materials is directly proportional to oxygen concentration. We can use Oxygen sensors to continuously monitor concentration levels in the observed areas. Uniformity is maintained in the observed areas by purging with Nitrogen due to its ability to reduce Oxygen concentration levels. Nitrogen can either be pumped from some external source or can be generated by membrane technology or activated carbon. This shall help reduce the oxygen and toxic concentration that can help people enter the affected area for a quick and fast repair by following the OSHA regulations [26].

Fire Triangle

Principle to break the fire triangle



Risk on Nitrogen Purging: Anything above the safety threshold concentration can prove to be harmful. Despite the gas being used for purging and tank blanketing, Nitrogen is a hazardous gas and must be handled with care. Exposure to high concentrations can lead to choking, physical and mental impairment and dizziness. According to the OSHA safety recommendation employees must work in workplace with O_2 concentrations ranging from 19.5% to 24%. All personnel are trained on the use of PPE but recommendations such as MineARC are already in place to monitor hazardous gases, including Nitrogen to which they are either fixed or are portable (e.g Aura-PT). SCSRs are also provided to provide safe escape from hazardous areas as they provide 30 to 70 minutes of breathable air in case of emergency response [29].

Inference

The introduction of safeguards in the process doesn't mean that the process is completely safe. The hazards might be caused due to off specification, pressure and temperature fluctuations, tank ruptures, valve malfunctions etc. To prevent incidents from recurring, "Central Board of Investigations (CSB)" urges companies to revise "Standard Operating Procedures (SOP)" to make the operation "easy to do the right and hard to do the wrong" method. This can be done by regular system checking, setting up monitoring levels (flow rate, gas release, and level), alarms in the areas that are prone to be affected and valves connected to drain hazardous material away from personnel. Regular updates to evaluate and strengthen process safety culture should be implemented by adapting appropriate practice guidance published by the Center for Chemical Process Safety and to set up robust safety management system to handle reactive chemicals by identifying, evaluating and controlling.

Conclusion

Presently Hydrogen is relishing its unprecedented momentum. The extensive and independent research determines the future of hydrogen and its crucial role. The decrease in fossil fuel reserves raises concerns to meet growing energy demand. By taking this into consideration, most researchers are now focusing on developing and relying on non-conventional resources that have emerged recently. Though there are multiple challenges such as cost, lack of differentiation, lack of hydrogen market, limited infrastructure, energy losses and policy effects that can hinder the efforts, still it is necessary to develop the non-conventional resources to sustain. There is also an unprecedented increase in the fuel cell market as noticed in a research conducted by Globaldata, that is not only related to PEM electrolyzers but also for other fuel cells, such as Phosphoric Acid Fuel Cell (PAFC). Researches are still being done on both low and high temperature PEM. Among the categories of PEM, the hydrocarbon-based has highest performance than other bio-inspired PEM. Enhancements to the PEM are considered on the basis of mechanical strength, proton conductivity and simple performance boost on membrane, electrodes or the whole membrane electrode assembly. Although sufficient research has been conducted on the PEM and its process; it can be further explored in areas such as leakage severity which will require specification and data of each equipment, pipeline and tubing. Also implement changes in the HAZOP study by implementing the design, operating conditions and by developing a safety mechanism to deal with security breach such as cyberattacks. All in all, “safety practices and hazard analysis” plays a vital role in the advancement of PEM electrolyzer that results in higher hydrogen yield.

Appendix

Table 2. Hydrogen Type & Production Methods

Hydrogen Type	Source	Method
Grey Hydrogen	Fossil Fuels (Natural Gas / Coal)	Pyrolysis, Gasification, Coal Gasification, Steam Reforming, Membrane Reactors, Partial Oxidation, CO2 Dry Reforming
Blue Hydrogen	Fossil Fuels (Natural Gas / Coal) with CO2 Sequestration	Coal Gasification, Steam Reforming, Membrane Reactors
Green Hydrogen	Hydrogen Produced from Electricity of Renewables	Electrolysis
Black Hydrogen	Bituminous Coal	Coal Gasification
Brown Hydrogen	Lignite	Coal Gasification
Red Hydrogen	Water	High-temperature Catalytic Splitting of Water using High Temperature
Pink Hydrogen	Water and Nuclear Power	Electrolysis
Yellow Hydrogen	Water and Solar Power	Electrolysis

Fig 6. Nafion Membrane

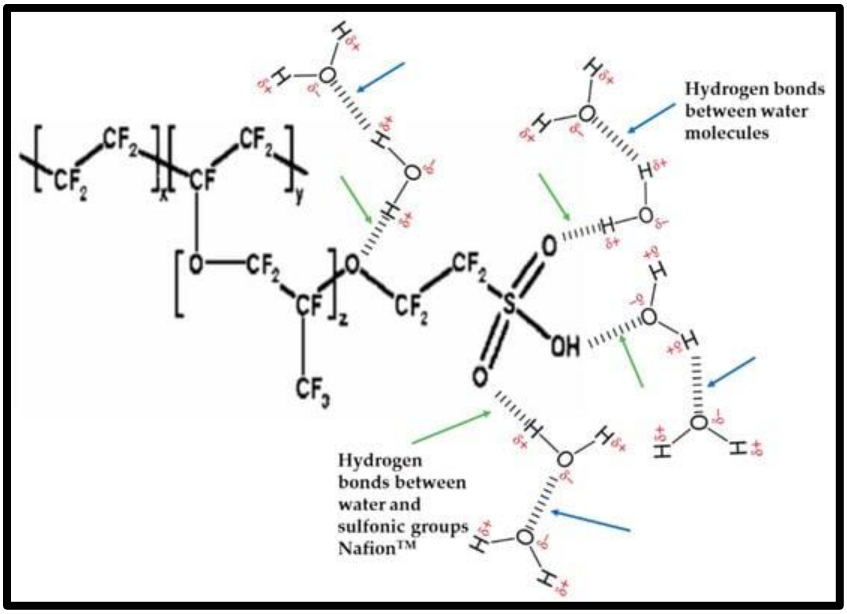


Fig 7. Polybenzimidazole Membrane

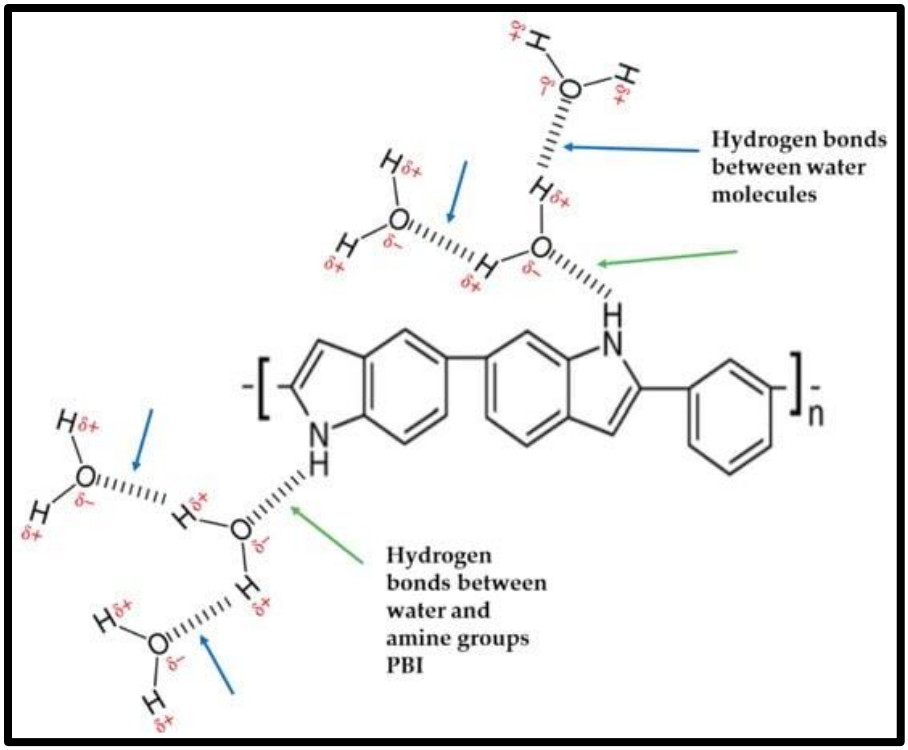


Fig 8. Sulfonated Poly Arylene Ether Ketone (SPEEK) Membrane

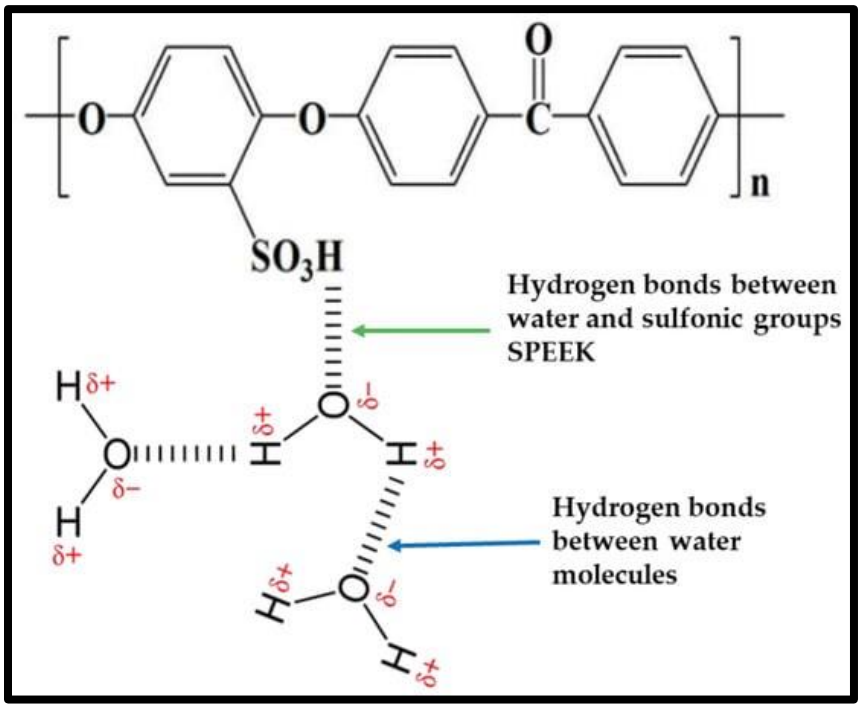


Fig 9. Polyimide Membrane

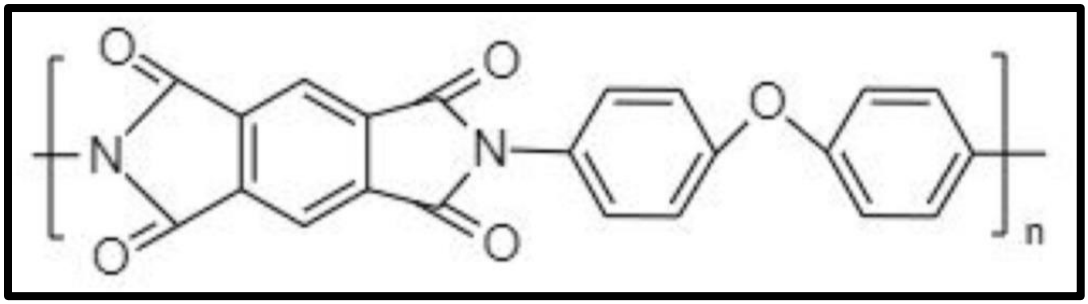


Table 3: Comparison of LT-PEMs based on thickness, water uptake, In-Exchange Capacity (IEC), Proton Conductivity and Power Density

Sl No.	Membrane	Operating Condition			Thickness (μm)	Water Uptake (%)
		Pressure (atm) (*MPa)	Temperature (°C)	Relative humidity (RH) (%)		
1	Nafion	1	25	-	183	33
2	BPSH-BPS	-	80	-	-	60
3	BisAF-BPSH	-	80	-	150	71
4	Nafion 117-Ce	-	60	70	-	26.4
5	Nafion+CeO2	1	90	100	35	
6	Nafion+CeO2	1	70	100	160	25.9
7	SPEEK	1	25		300	600
8	SPEEK/BPO4	1	25	100	200	116
9	SPEEK	-	25	100	82	120
10	SPEEK/PSSA-g-PVDF	-	65	50	50	35
11	AP6FSPEEK		80	100	-	69.3
12	SPEEK/NIM-SiO2	0.1*	60	100	110 – 130	52.6
13	C-SPAKES/Im-MOF-801-4	-	90	100	-	12.5
14	SPAES50	1	30	45	20	27.2

1atm=0.1Mpa

Sl. No	Membrane	Conductivity (mS/cm)	IEC (meq/g) (*mmol.gm)	Power density (mW/cm^2)
1	Nafion	35	0.93	126.04
2	BPSH-BPS	95	1.28	-
3	BisAF-BPSH	130	1.6	-
4	Nafion 117-Ce	-	0.89*	433
5	Nafion+CeO2	88.3	-	-
6	Nafion+CeO2	176	0.84*	120
7	SPEEK	10	1.95	-
8	SPEEK/BPO4	6.1	-	-
9	SPEEK	16.8	2.3	-
10	SPEEK/PSSA-g-PVDF	720	-	470.52
11	AP6FSPEEK	87	1.65*	-
12	SPEEK/NIM-SiO2	220	1.73*	92.8
13	C-SPAKES/Im-MOF-801-4	66	0.68*	15.5
14	SPAES50	112.3	1.89	-

Table 4: Summary of Hydrogen Production By Water Splitting Technologies along with the types of diaphragm/membrane used, advantages, disadvantages, and efficiencies

Water Splitting Technologies	Advantages	Disadvantages	Efficiency
Alkaline Type of diaphragm: porous inorganic (asbestos, ceramic, cement)	Well established technology Economical, Very durable Operates at low temperature (30–80 °C) Inexpensive electro catalyst	High concentration corrosive electrolytes Limited current density (below 400 mA/cm2), Low operating pressure Low energy efficiency, Low gas purity	60– 80%
Solid oxide Types of membranes: oxygen ion ceramic electrolyte membrane, YSZ	Dual-function fuel cell and Electrolyzer Superior ionic conductivity Ultrapure hydrogen Excellent efficiency	Very high operating temperature (500–850 °C), Energy intensive process and not economical, Low durability (stability and degradation)Still immature technology—lab scale	90 – ~100%
PEM Type of membranes: Nafion, PBI, SPEEK, polyethylene	High hydrogen purity (up to 99.995%), High current density, High voltage efficiency, Dynamic operation	High-cost catalysts, Mildly durable Costly membrane, More expensive stack materials compared to alkaline Partially established technology	55 – 70%
AEM Types of membranes: A201 membrane, Selenion AMV, A901 membrane	Lower cost of catalysts Inexpensive stack components -(Nickel-based)	Low ionic conductivity Early stage of development Low power efficiency Low membrane stability Large Ohmic resistance loss Large catalyst loading	50–70%
Acid-alkaline amphoteric Types of membranes: bipolar membrane, acid-doped PBI-based membranes, Nafion	Reduced energy consumption, Reduced over potential, Hydrogen production four times that of alkaline electrolysis	Increased membrane resistance Need to use bipolar ion-exchange membrane, Need to use both acidic and alkaline electrolytes	~100%
Microbial, Types of membranes: SPAES * / polyimide, SPEEK, SPEEK/PES, Nafion, AMI-7001, bipolar membranes, charge-mosaic membranes, microporous membranes	Requires only a low external voltage Uses organic materials	Still under development High internal resistance Complicated design Low rates of hydrogen production Fabrication and operational costs are high	60–70%
Photo electrochemical Types of membranes: polyamide, Nafion based membrane	Direct solar to hydrogen conversion Simpler setup	Low conversion factor Low hydrogen production Still at infancy stage	<10%

Table 5. Pipeline Material

Pipeline Number	Material	Stream	Exit	Entry
1	Pretreated Feed (water)	Liquid	Reservoir/storage tank	Mixer
2	Water (Mixed)	Liquid	Mixer	Pump
3	Water (Pretreated Feed)	Liquid	Pump	Sediment Filter
4	Sediment (solids)	Mixed	Sediment Filter	Waste
5	Water	Liquid	Sediment Filter	Pump
6	Water (Treated)	Liquid	Separator	Pump
7	Water (Treated)	Liquid	Pump	Ion Exchanger
8	Water (Treated)	Liquid	Ion Exchanger	Carbon Filter
9	Carbon	Mixed	Carbon Filter	-
10	Water	Liquid	Carbon Filter	Heat Exchanger
11	Water (Heated)	Liquid	Heat Exchanger	Anion Electrode (PEM stack)
12	Water+O2 (Mix Stream)	Mixed	Anion Electrode (PEM Stack)	Separator
13	O2	Vapor	Separator	Control Valve
14	O2	Vapor	Control Valve	-
15	H2+H2O	Mix	Cathode Electrode (PEM Stack)	Extractor
16	H2O	Liquid	Extractor	-
17	H2	Vapor	Extractor	Dryer
18	H2	Vapor	Dryer	Extractor
19	H2	Vapor	Storage Tank	Compressor
20	H2	Vapor	Compressor	Control Valve
21	H2	Vapor	Control valve	Exit Pipeline

Table 6. Equipment

Sl No.	Equipment Number	Name
1	B1	Mixer
2	B2	Pump
3	B3	Sediment Filter
4	B4	Extractor
5	B5	Control Valve
6	B6	Ion Exchanger
7	B7	Control Valve
8	B8	Carbon Filter
9	B9	Heat Exchanger
10	B10	Anion Electrode
11	B11	Cathode Electrode
12	B12	PEM Stack
13	B13	Extractor
14	B14	-
15	B15	Dryer
16	B16	H2 Storage
17	B17	Compressor
18	B18	Control Valve

Table 7. Failure Mode Analysis

Sl No.	FMEA failure mode	
1	Hydrogen embrittlement	Open/close failure of automatic valve
2	Cholride stress corrosion cracking	Open/close failure of control valve
3	Corrosion	Open/Close failure of check valve
4	Fatigue	Pressure indicator failure
5	Loosening of threaded joints	Temperature indicator failure
6	Weld Defect	Safety valve failure
7	Defect	Filter clogging
8	Deterioration of sealing material	Filter damage
9	Gland leakage	Start/stop failure
10	Seat leakage	Voltage indicator failure
11	Damage of Nafion membrane	

Fig 10. HAZOP Methodology

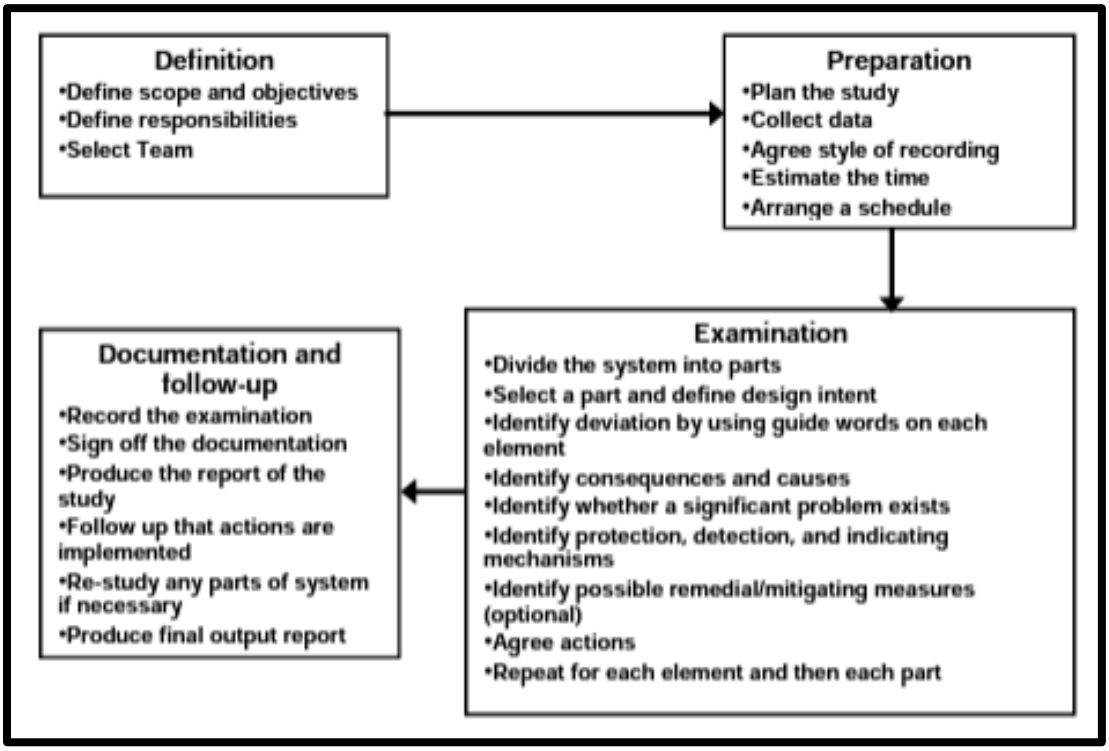


Fig 11. Generic Severity Rating Scale

Severity Rating Scale		
Rating	**Description**	**Definition (Severity of Effect)**
10	Dangerously high	Failure could injure the customer or an employee.
9	Extremely high	Failure would create noncompliance with federal regulations.
8	Very high	Failure renders the unit inoperable or unfit for use.
7	High	Failure causes a high degree of customer dissatisfaction.
6	Moderate	Failure results in a subsystem or partial malfunction of the product.
5	Low	Failure creates enough of a performance loss to cause the customer to complain.
4	Very Low	Failure can be overcome with modifications to the customer's process or product, but there is minor performance loss.
3	Minor	Failure would create a minor nuisance to the customer, but the customer can overcome it without performance loss.
2	Very Minor	Failure may not be readily apparent to the customer, but would have minor effects on the customer's process or product.
1	None	Failure would not be noticeable to the customer and would not affect the customer's process or product.

Table 8. HAZOP Worksheet

PHA Worksheets

Node 1: (Liquid Stream) Reservoir, Mixer, Pump, sediment Filter, H2O-O2 separator

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
1.1. High Pressure	1.1.1. Potential overpressure at the separator. Potential loss of mechanical integrity. Potential rupture of the separator resulting in large release of gas and liquid to which can cause fire upon contact to an ignition source.	1.1.1.1. Operates above the equipment design pressure.	6. install a spill back to the low pressure separator	2	
			3. Operator response to high pressure alarm		
			2. Install a pressure gauge on the upstream and on the separator		
			1. High Integrity Pressure Protection Systems		
		1.1.1.2. External fire in the vicinity of the separator	5. High pressure shutdown		
			4. Install a thermal expansion relief on the valved section		
			2. Install a pressure gauge on the upstream and on the separator		
			3. Operator response to high pressure alarm		

1.2. Low Pressure	1.2.1. Potential loss of light and intermediate components lost to the gas phase in the separator resulting in less liquid.	1.2.1.1. Pipeline leak or rupture	9. operator response to low pressure alarm	2	
			8. low flow shutdown		
			7. Low pressure shutdown		
		1.2.1.2. Fitting and flanges leakage	9. operator response to low pressure alarm		
			8. low flow shutdown		
			7. Low pressure shutdown		
		1.2.1.3. control valve failure	9. operator response to low pressure alarm		
			8. low flow shutdown		
			11. low pressure shutdown		
			10. increase backup pump		
		1.2.1.4. increase in pumping capacity	8. low flow shutdown		
			7. Low pressure shutdown		
			9. operator response to low pressure alarm		
			12. revision on the design specification on the pump		
1.3. High Temperature	1.3.1. High pressure builds up in the transfer line and separator.	1.3.1.1. Cooler failure	16. Operator response to high temperature alarm	2	
			15. release pressure relief valve		
			14. Regular system checking		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
			13. Install temperature sensor and alarm		
		1.3.1.2. High intermediate storage temperature	16. Operator response to high temperature alarm		
			15. release pressure relief valve		
			14. Regular system checking		
			13. Install temperature sensor and alarm		
		1.3.1.3. Pressure indicator failure	16. Operator response to high temperature alarm		
			15. release pressure relief valve		
			14. Regular system checking		
			13. Install temperature sensor and alarm		
	1.3.2. Difficult to control the reaction	1.3.2.1. Temperature controller failure	16. Operator response to high temperature alarm	2	
			15. release pressure relief valve		
			14. Regular system checking		
			13. Install temperature sensor and alarm		
			17. An automatic shutdown of the reactor when its temperature increases abnormally.		

1.4. Low Temperature	1.4.1. Water sump and drain line freeze up.	1.4.1.1. Low power supply	17. An automatic shutdown of the reactor when its temperature increases abnormally.	2	
			20. Operator response to low temperature alarm		
			19. supply enough energy		
			13. Install temperature sensor and alarm		
			18. Install temperature transmitter		
		1.4.1.2. Winter freeze	17. An automatic shutdown of the reactor when its temperature increases abnormally.		
			20. Operator response to low temperature alarm		
			19. supply enough energy		
			13. Install temperature sensor and alarm		
			18. Install temperature transmitter		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
		1.4.1.3. Heating element dysfunction	17. An automatic shutdown of the reactor when its temperature increases abnormally.		
			20. Operator response to low temperature alarm		
			13. Install temperature sensor and alarm		
			18. Install temperature transmitter		
		1.4.1.4. Excessive heat transfer	17. An automatic shutdown of the reactor when its temperature increases abnormally.		
			20. Operator response to low temperature alarm		
			13. Install temperature sensor and alarm		
			18. Install temperature transmitter		

1.5. High Level	1.5.1. Potential overfill of the separator will leak into the O2 export pipeline. Potential for off-spec product.	1.5.1.1. Liquid outlet is closed	25. Install a backup drain	2	
			24. High level Shutdown		
			14. Regular system checking		
			23. Operator response to high level alarm		
			22. Monitor the flow rate		
		1.5.1.2. Blockage in vapor stream	24. High level Shutdown		
			14. Regular system checking		
			23. Operator response to high level alarm		
			22. Monitor the flow rate		
		1.5.1.3. Failure of shutdown valve	14. Regular system checking		
			23. Operator response to high level alarm		
			22. Monitor the flow rate		
			26. Install a secondary backup valve/pump/route		
		1.5.1.4. Too high flow rate of recycle for mixer	23. Operator response to high level alarm		
			24. High level Shutdown		
			14. Regular system checking		
			21. Monitor the flow rate of recycle		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
1.6. Low Level	1.6.1. Potential for loss of mechanical integrity. Potential for rupture of vessel or associated piping.	1.6.1.1. Valve is partially closed	31. Install a level indicator and controller	2	3. Interlock to be configured to stop transfer pump on desired equipment
			28. low level shutdown		
			27. Operator response to low level alarm		
			30. install a backup valve		
		1.6.1.2. Pipeline is partly blocked	32. install a backup pathway or a secondary route		
			14. Regular system checking		
			29. monitor the flow rate		
			28. low level shutdown		
			27. Operator response to low level alarm		
			31. Install a level indicator and controller		
		1.6.1.3. Pump is not in full operation	14. Regular system checking		
			29. monitor the flow rate		
			28. low level shutdown		
			31. Install a level indicator and controller		
			27. Operator response to low level alarm		
		1.6.1.4. Too low flow rate of recycle for mixer	27. Operator response to low level alarm		
			14. Regular system checking		
			21. Monitor the flow rate of recycle		

1.7. High Flow	1.7.1. The mixture is not properly separated. Decrease product quality. Decrease efficiency of sediment filter.	1.7.1.1. Delivery pump malfunctions	37. Monitor the flow into the separator	2	
			36. Operator response to high flow alarm		
			14. Regular system checking		
			35. Install high level indicator		
			34. install independent level transmitter		
			33. Install automatic pump shutdown		
		1.7.1.2. Control valve failure	37. Monitor the flow into the separator		
			36. Operator response to high flow alarm		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
			14. Regular system checking		
			35. Install high level indicator		
			34. install independent level transmitter		
			33. Install automatic pump shutdown		
		1.7.1.3. level control fails	37. Monitor the flow into the separator		
			36. Operator response to high flow alarm		
			14. Regular system checking		
			35. Install high level indicator		
			34. install independent level transmitter		
			33. Install automatic pump shutdown		

1.8. Low Flow	1.8.1. Low supply of mixture, rate of reaction decrease	1.8.1.1. Pipe leakage	41. Monitor the flow rate of the recycle for mixer	2	
			39. operator response to low flow alarm		
			40. install low flow indicator		
			14. Regular system checking		
			38. Monitor the flow out of the separator		
			42. Material loss		
		1.8.1.2. Flange leakage	41. Monitor the flow rate of the recycle for mixer		
			39. operator response to low flow alarm		
			40. install low flow indicator		
			14. Regular system checking		
			38. Monitor the flow out of the separator		
			42. Material loss		
		1.8.1.3. Pump malfunction	41. Monitor the flow rate of the recycle for mixer		
			39. operator response to low flow alarm		
			40. install low flow indicator		
			14. Regular system checking		
			38. Monitor the flow out of the		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
			separator		
			42. Material loss		
		1.8.1.4. Level control fails	41. Monitor the flow rate of the recycle for mixer		
			39. operator response to low flow alarm		
			40. install low flow indicator		
			14. Regular system checking		
			38. Monitor the flow out of the separator		
1.9. No Flow	1.9.1. Loss of feed to the separator. Pump overheats. Potential discharge outside	1.9.1.1. Supply tank is empty	45. ensure good communication with intermediate storage operator	2	
		1.9.1.2. Pumps fail to run	14. Regular system checking		
			43. Operator response to low flow alarm		
			47. Check design specification (revision needed)		
			46. Install a low level alarm		
		1.9.1.3. Pipeline is fractured	14. Regular system checking		
			43. Operator response to low flow alarm		
			46. Install a low level alarm		
		1.9.1.4. Valve is closed	49. Install a backup route to redirect the flow		
			43. Operator response to low flow alarm		
			14. Regular system checking		
1.10. Composition	1.10.1. Contaminated water, decrease in efficiency of the separator, product not achieved	1.10.1.1. pipeline fracture	48. Constant water quality checking	2	
			14. Regular system checking		

Node 2: (Vapor Stream) O2 vented out from the extractor

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
2.1. High Pressure	2.1.1. Poor Separation, Potential pressure equilibrium from separator to the gas export line, potential over pressurization of discharge piping, rupture of tubes, potential loss of mechanical integrity, potential fire and explosion, oxygen rich environment affect the PPE, potential internal damage to the compressor.	2.1.1.1. utility malfunction	51. Install a pressure relief valve		
			3. Operator response to high pressure alarm		
			50. Install a pressure gauge		
		2.1.1.2. Pressure indicator fails	5. High pressure shutdown		
			3. Operator response to high pressure alarm		
			51. Install a pressure relief valve		
		2.1.1.3. Inadvertent closure of SIS valve downstream	54. valve can be made of elastomers due to its low ignition energies than metals		
			53. Gas detection alarm		
			5. High pressure shutdown		
			3. Operator response to high pressure alarm		
			51. Install a pressure relief valve		

2.2. Low Pressure	2.2.1. Potential vacuum conditions, potential valve damage, commercial issue with asset damage.	2.2.1.1. Shutdown valve fails	3. Operator response to high pressure alarm		
			5. High pressure shutdown		
		2.2.1.2. Level indicator fails affecting the control valve	3. Operator response to high pressure alarm		
			5. High pressure shutdown		
		2.2.1.3. Inadvertent closure of shutdown valve	60. Automated low pressure shutdown upstream of the separator		
			3. Operator response to high pressure alarm		
			5. High pressure shutdown		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
2.3. High Temperature	2.3.1. Potential instrument damage. Potential fire/explosion. High pressure in the transfer line. Potential Oxygen leakage	2.3.1.1. Temperature controller failure	126. Oxygen gas detectors		11. Consider vented deflagration panels.
			58. install thermal expansion relief valve		
			16. Operator response to high temperature alarm		
			55. High temperature shutdown		
		2.3.1.2. Utility failure	126. Oxygen gas detectors		
			58. install thermal expansion relief valve		
			16. Operator response to high temperature alarm		
			55. High temperature shutdown		
			127. Secondary backup cooler		

2.4. Low Temperature	2.4.1. Pipeline will freeze up. Decrease in flow out. O_2 vapor concentration increases.	2.4.1.1. Winter freeze	20. Operator response to low temperature alarm		
			59. Install temperature indicator		
2.5. High Level	2.5.1. Potential overfills of the separator with liquid flow to the gas export pipeline.	2.5.1.1. Blockage at the outlet stream	14. Regular system checking		
			23. Operator response to high level alarm		
			62. Install level controller		
			61. Install level indicator		
2.6. Low Level	2.6.1. Potential for gas blow by into the separator causing overpressure. Potential loss of mechanical integrity. Potential rupture of vessel or associated piping. Potential fire/explosion	2.6.1.1. inlet stream leakage	126. Oxygen gas detectors		
			14. Regular system checking		
			63. Fit low level alarm		
			27. Operator response to low		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
			level alarm		
		2.6.1.2. faulty level control measurement	14. Regular system checking		
			27. Operator response to low level alarm		
2.7. High Flow	2.7.1. Potential accumulation of vapor resulting in overpressure of separator, potential rupture of vessel resulting in release of vapor potential fire/explosion	2.7.1.1. failure of flow indicator controller causing the flow valve to open	14. Regular system checking		
			15. release pressure relief valve		
			3. Operator response to high pressure alarm		
			5. High pressure shutdown		
2.8. Low Flow	2.8.1. No credible safety hazard identified	2.8.1.1. No additional causes			
2.9. No Flow	2.9.1. O2 cannot be vented. Separator will over pressurize and rupture due to no means of release. O2 mixes back with H2 causing explosion	2.9.1.1. Blockage at the gas export line and the separator outlet	66. install pressure relief valve		
			67. Install a secondary backup route to vent out the gas		
			65. install flow controller		
			64. Install flow indicator		
			14. Regular system checking		

2.10. Composition	2.10.1. Potential of large flammable gas and liquid release to atmosphere, potential significant commercial and environmental impacts	2.10.1.1. Introduction of gas into the liquid stream due to rupture	14. Regular system checking		
			57. Install fans for dilution of flammable gas		
			53. Gas detection alarm		
			56. valves and piping made of elastomers due to low ignition temperature		

Node 3: (Liquid Stream) Separator, Pump, Ion Exchange Filter, Absorber, Heat Exchanger, Proton Exchange Membrane Stack.

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
3.1. High Pressure	3.1.1. Potential deadheading of pumps resulting in pump damage due to overheating. Commercial issue with asset damage. Poor Separation. Flooding/leakage hazards. Potential fire/explosion. Transfer line subjected to full pump delivery or surge pressure. Burst and release of gases to surroundings. Potential contamination of the oxygen-water line with possible overpressure.	3.1.1.1. Flooding	5. High pressure shutdown	2	6. In case of water spill Firefighters' protective clothing gloves, helmet, running or bunker coat, running or bunker pants. Protects against heat, hot water, and some particles.
			68. Install flow indicator to provide spillback to the separator		
			16. Operator response to high temperature alarm		
		3.1.1.2. Isolation valve closed in error or level controller valve failure	16. Operator response to high temperature alarm		
			5. High pressure shutdown		
			14. Regular system checking		
			68. Install flow indicator to provide spillback to the separator		
		3.1.1.3. Valve failure	16. Operator response to high temperature alarm		
			5. High pressure shutdown		
			14. Regular system checking		
			68. Install flow indicator to provide spillback to the separator		

		3.1.1.4. Pump Failure	16. Operator response to high temperature alarm		
			5. High pressure shutdown		
			14. Regular system checking		
			68. Install flow indicator to provide spillback to the separator		
		3.1.1.5. Flow indicator failure	16. Operator response to high temperature alarm		
			5. High pressure shutdown		
			14. Regular system checking		
			68. Install flow indicator to provide spillback to the separator		
		3.1.1.6. Shutdown valve inadvertent closure	16. Operator response to high temperature alarm		
			5. High pressure shutdown		
			14. Regular system checking		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
			68. Install flow indicator to provide spillback to the separator		
		3.1.1.7. O2/H20 pipeline rupture	14. Regular system checking		
			133. Combustible gas sensor shuts down the Electrolyzer		

3.2. Low Pressure	3.2.1. Potential pump cavitation resulting in pump damage. Commercial issue with asset damage. Product cannot be removed. Not achieved desired operations.	3.2.1.1. Unstable condition	70. Install pressure indicator and controller	2	
			43. Operator response to low flow alarm		
			69. Low pressure shutdown		
		3.2.1.2. Increase pump capacity	70. Install pressure indicator and controller		
			43. Operator response to low flow alarm		
			69. Low pressure shutdown		
		3.2.1.3. Failure of shutdown valve	70. Install pressure indicator and controller		
			43. Operator response to low flow alarm		
			69. Low pressure shutdown		
		3.2.1.4. Valve blocked in pump suction	70. Install pressure indicator and controller		
			43. Operator response to low flow alarm		
			69. Low pressure shutdown		
3.3. High Temperature	3.3.1. Difficult to remove excess heat	3.3.1.1. Temperature control failure	20. Operator response to low temperature alarm	2	4. It is to be ensured that individual air suction blower to heat exchanger should be stopped on High Temperature.
			59. Install temperature indicator		
			18. Install temperature transmitter		
	3.3.2. difficult to control reaction, Lower yield, Increase production cost	3.3.2.1. Failure in cooler	14. Regular system checking	2	
			20. Operator response to low temperature alarm		
			59. Install temperature indicator		
			18. Install temperature transmitter		
		3.3.2.2.	14. Regular system		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
		Superheated steam supply	checking		
			20. Operator response to low temperature alarm		
			59. Install temperature indicator		
			18. Install temperature transmitter		
3.4. Low Temperature	3.4.1. Poor separation	3.4.1.1. Heating system malfunction	20. Operator response to low temperature alarm	2	
			14. Regular system checking		
			72. Increase heat duty of heating		
			71. Monitor the temperature of the tank		
3.5. High Level	3.5.1. Accumulation in the equipment, flooding/leaking hazards	3.5.1.1. Excessive feed	22. Monitor the flow rate	2	
			62. Install level controller		
			74. install level indicator		
			23. Operator response to high level alarm		
			64. Install flow indicator		
		3.5.1.2. Flow level controller failed	14. Regular system checking		
		3.5.1.3. Blockage in vapor stream	22. Monitor the flow rate		
			23. Operator response to high level alarm		
			14. Regular system checking		
			75. Monitor the level		

3.6. Low Level	3.6.1. Increase production cost, backflow of material	3.6.1.1. Pump malfunction	78. Install monitoring system	2	
			27. Operator response to low level alarm		
			26. Install a secondary backup valve/pump/route		
			77. Fast repair of the pipe leaking		
			76. Regular pipe cleaning		
		3.6.1.2. Pipe blockage	78. Install monitoring system		
			27. Operator response to		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
			low level alarm		
			26. Install a secondary backup valve/pump/route		
			77. Fast repair of the pipe leaking		
			76. Regular pipe cleaning		
		3.6.1.3. Pipe leaking	78. Install monitoring system		
			27. Operator response to low level alarm		
			26. Install a secondary backup valve/pump/route		
			77. Fast repair of the pipe leaking		
			76. Regular pipe cleaning		
		3.6.1.4. level controller malfunction	78. Install monitoring system		
			27. Operator response to low level alarm		
			26. Install a secondary backup valve/pump/route		
			77. Fast repair of the pipe leaking		
			76. Regular pipe cleaning		
			79. Increase the feed flow		

3.7. High Flow	3.7.1. Difficult to control the heating process, more reactants go to the reactor, incomplete reaction, pump damage, commercial issue with asset damage.	3.7.1.1. failure in operation monitor	5. High pressure shutdown	2	2. Interlock to be configured to stop feeding system on High difference in weight.
			81. Install control valve		
			36. Operator response to high flow alarm		
			14. Regular system checking		
			80. Install high flow detector and alarm		
		3.7.1.2. More flow in the stream	7. Low pressure shutdown		
			5. High pressure shutdown		
			81. Install control valve		
			36. Operator response to high flow alarm		
			14. Regular system checking		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
			80. Install high flow detector and alarm		
		3.7.1.3. low pressure in the export pipeline due to a leak or rupture	7. Low pressure shutdown		
			5. High pressure shutdown		
			81. Install control valve		
			36. Operator response to high flow alarm		
			14. Regular system checking		
			80. Install high flow detector and alarm		

3.8. Low Flow	3.8.1. Waste time and energy, increase production cost, rate of reaction decrease, decrease product concentration, and pump cavitation.	3.8.1.1. Pump malfunction	22. Monitor the flow rate	2	
			14. Regular system checking		
			39. operator response to low flow alarm		
			78. Install monitoring system		
			82. change the leaking pipe		
			77. Fast repair of the pipe leaking		
			76. Regular pipe cleaning		
		3.8.1.2. pipe blockage	22. Monitor the flow rate		
			14. Regular system checking		
			39. operator response to low flow alarm		
			78. Install monitoring system		
			82. change the leaking pipe		
			77. Fast repair of the pipe leaking		
			76. Regular pipe cleaning		
		3.8.1.3. pipe leaking	22. Monitor the flow rate		
			14. Regular system checking		
			39. operator response to low flow alarm		
			78. Install monitoring system		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
			82. change the leaking pipe		
			77. Fast repair of the pipe leaking		
			76. Regular pipe cleaning		
		3.8.1.4. Low supply of mixture	22. Monitor the flow rate		
			14. Regular system checking		
			39. operator response to low flow alarm		
			78. Install monitoring system		
			82. change the leaking pipe		
			77. Fast repair of the pipe leaking		
			76. Regular pipe cleaning		

3.9. No Flow	3.9.1. No steam or air supply, waste time, cost and energy, no supply of feed and product.	3.9.1.1. Pump failure	43. Operator response to low flow alarm	2	
			73. Install backup pump		
			14. Regular system checking		
			85. install control valve		
		3.9.1.2. Pipe rupture	43. Operator response to low flow alarm		
			73. Install backup pump		
			14. Regular system checking		
			85. install control valve		
		3.9.1.3. Cooler failure	43. Operator response to low flow alarm		
			73. Install backup pump		
			14. Regular system checking		
			85. install control valve		
		3.9.1.4. valve is closed	43. Operator response to low flow alarm		
			73. Install backup pump		
			14. Regular system checking		
			85. install control valve		
		3.9.1.5. Pipe	43. Operator response to		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
		blockage to PEM	low flow alarm		
			73. Install backup pump		
			14. Regular system checking		
			85. install control valve		
			86. secondary backup route to the PEM		
3.10. Composition	3.10.1. Potential export pump cavitation, potential pump damage, commercial issue with asset damage, contamination at the absorber or the deionizer	3.10.1.1. Poor separation	14. Regular system checking	2	
			43. Operator response to low flow alarm		
			69. Low pressure shutdown		
		3.10.1.2. NPSH is too low	14. Regular system checking		
			43. Operator response to low flow alarm		
			69. Low pressure shutdown		
		3.10.1.3. Deionizer fails	84. automated shutdown to the operation.		
			83. secondary route or a backup		
			14. Regular system checking		
3.11. Electrical loss	3.11.1. Poor separation, loss of feed to the equipment.	3.11.1.1. Mixer failure	87. Check on agitation	2	
			14. Regular system checking		
		3.11.1.2. Pump failure	88. operator response to alarm		
			14. Regular system checking		
			84. automated shutdown to the operation.		
	3.11.2. Static Charge generation	3.11.2.1. Over-voltage	135. Consider a backup DC-DC rectifier	2	1. Consider providing Human static discharge point near the rectifier or electrical subsystems and SOP to incorporate the same

Node 4: (Mixed Stream) PEM Stack, Stream Splitter, 2-Bed Dryer, H2 Storage, Gas Compressor, Gas Export Pipeline					
Deviation	**Consequence**	**Cause**	**Safeguard**	**L**	**PHA Recommendation**
4.1. High Pressure	4.1.1. Potential hydrogen release, potential fire/explosion, PEM stack fails, Potential spillback to the PEM stack due to over pressurization, potential loss of mechanical integrity, potential rupture, potential internal damage to dryer, poor separation. Possible to send wet H2 downstream to users with impact downstream.	4.1.1.1. Valve closed and pump failure	14. Regular system checking	2	7. Consider revision of API standard RP 520 (Recommended Practice for Sizing, Selection, and Installation of Pressure Relieving Devices) or NFPA 497 (Recommended Practice for the Classification of Flammable Liquids, Gases or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas) mainly used to classify hazardous areas. Consider adding vented deflagration panels Consider vent design as per NFPA 2 standards
			128. Hydrogen Gas detection alarm		
			53. Gas detection alarm		
			3. Operator response to high pressure alarm		
			5. High pressure shutdown		
			89. Install pressure relief valve		
		4.1.1.2. Inadvertent closure to the SIS valve	128. Hydrogen Gas detection alarm		
			14. Regular system checking		
			53. Gas detection alarm		
			3. Operator response to high pressure alarm		
			5. High pressure shutdown		
			89. Install pressure relief valve		

		4.1.1.3. Pressure indicator failure	128. Hydrogen Gas detection alarm		
			14. Regular system checking		
			53. Gas detection alarm		
			3. Operator response to high pressure alarm		
			5. High pressure shutdown		
			89. Install pressure relief valve		
		4.1.1.4. Steam utility malfunction	128. Hydrogen Gas detection alarm		
			91. Lower the reboiler duty		
			90. Install pressure gauge		

			14. Regular system checking		
			53. Gas detection alarm		
			3. Operator response to high pressure alarm		
			5. High pressure shutdown		
			89. Install pressure relief valve		
		4.1.1.5. Loss of containment from Hydrogen storage tank	128. Hydrogen Gas detection alarm		
			119. Pressure switch to shut down the compressor		
			118. Combustible gas detector		
			117. Pressure relief valve on Hydrogen Compressor		
			116. Pressure Indicator on discharge line		
			115. Install a pressure and pressure Switch on Hydrogen compressor.		
		4.1.1.6. Drains on H2 separator left closed	130. Install pressure controller and indicator		
			129. Install a secondary drain as backup		

4.2. Low Pressure	4.2.1. Product cannot be removed, undesirable operations	4.2.1.1. Increase pumping capacity	9. operator response to low pressure alarm	2	
			14. Regular system checking		
			93. Install low pressure alarm along with the PIC		
			92. Install pressure controller		
			73. Install backup pump		
		4.2.1.2. Unstable condition	14. Regular system checking		
			53. Gas detection alarm		
			3. Operator response to high pressure alarm		
			5. High pressure		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
			shutdown		
			89. Install pressure relief valve		

4.3. High Temperature	4.3.1. Difficult to remove excessive heat, steam become superheated, difficult to control reaction, accumulation in column, membrane becomes dehydrated reducing the efficiency of the PEM stack - Delamination, catalyst degradation.	4.3.1.1. Furnace malfunction	122. Increase the speed of the HVAC system	2	
			17. An automatic shutdown of the reactor when its temperature increases abnormally.		
			16. Operator response to high temperature alarm		
			14. Regular system checking		
			13. Install temperature sensor and alarm		
		4.3.1.2. Temperature control failure	131. Consider an explosion vent		
			17. An automatic shutdown of the reactor when its temperature increases abnormally.		
			16. Operator response to high temperature alarm		
			14. Regular system checking		
			13. Install temperature sensor and alarm		
		4.3.1.3. failure in cooler	17. An automatic shutdown of the reactor when its temperature increases abnormally.		
			16. Operator response to high temperature alarm		
			14. Regular system checking		
			13. Install temperature sensor and alarm		

		4.3.1.4. Lower yield	17. An automatic shutdown of the reactor when its temperature increases abnormally.		
			16. Operator response to high temperature alarm		
			14. Regular system checking		
			13. Install temperature sensor and alarm		
			95. Add inhibitor		
		4.3.1.5. Reboiler produced less heat	17. An automatic shutdown of the reactor when its temperature increases abnormally.		
			16. Operator response to high temperature alarm		
			14. Regular system checking		
			13. Install temperature sensor and alarm		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
		4.3.1.6. temperature controller malfunction	17. An automatic shutdown of the reactor when its temperature increases abnormally.		
			16. Operator response to high temperature alarm		
			14. Regular system checking		
			13. Install temperature sensor and alarm		

4.4. Low Temperature	4.4.1. Poor separation, low energy stream, reaction favor to reactant formation, rate of reaction decreases, and separation at the dryer becomes difficult.	4.4.1.1. Malfunction steam utility	102. Install TIC		
			101. adjust inlet flow temperature		
			100. Monitor the temperature		
			20. Operator response to low temperature alarm		
			14. Regular system checking		
			97. Increase reboiler duty		
			96. Temperature probe in reboiler		
		4.4.1.2. Too low heat duty of reboiler	102. Install TIC		
			100. Monitor the temperature		
			20. Operator response to low temperature alarm		
			14. Regular system checking		
			96. Temperature probe in reboiler		
			99. Increase heat duty of reboiler		
			98. Thermocouple of each stage		
		4.4.1.3. Furnace failure	102. Install TIC		
			100. Monitor the temperature		
			20. Operator response to low temperature alarm		
			14. Regular system checking		
			96. Temperature probe in reboiler		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
			99. Increase heat duty of reboiler		
			98. Thermocouple of each stage		
		4.4.1.4. Low power supply	102. Install TIC		
			100. Monitor the temperature		
			20. Operator response to low temperature alarm		
			14. Regular system checking		
			96. Temperature probe in reboiler		
			99. Increase heat duty of reboiler		
			98. Thermocouple of each stage		
		4.4.1.5. Excessive heat transfer by cooler	102. Install TIC		
			100. Monitor the temperature		
			20. Operator response to low temperature alarm		
			14. Regular system checking		
			96. Temperature probe in reboiler		
			99. Increase heat duty of reboiler		
			98. Thermocouple of each stage		

4.5. High Level	4.5.1. Potential overfills of the dryer, storage tank, PEM stack. Potential for off spec product, potential fire/explosion.	4.5.1.1. Failure of level controller	66. install pressure relief valve		5. Consider Flame/fire retardant coveralls normally worn as an undergarment. Provides protection from flash fires. Also can consider reviewing the IFC fire code (General fire protection code requirements. Special requirements for hydrogen occupancies are only required if hydrogen exceeds MAQ (maximum allowable quantity)).
			14. Regular system checking		
			23. Operator response to high level alarm		
			24. High level Shutdown		
		4.5.1.2. Valve is closed	66. install pressure relief valve		
			14. Regular system checking		
			23. Operator response to high level alarm		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
			24. High level Shutdown		
		4.5.1.3. Failure of shutdown valve	66. install pressure relief valve		
			14. Regular system checking		
			23. Operator response to high level alarm		
			24. High level Shutdown		
		4.5.1.4. Convective transfer caused by pressure gradient	66. install pressure relief valve		
			14. Regular system checking		
			23. Operator response to high level alarm		
			24. High level Shutdown		
		4.5.1.5. Back diffusion of water from the cathode to anode	66. install pressure relief valve		
			14. Regular system checking		
			23. Operator response to high level alarm		
			24. High level Shutdown		
		4.5.1.6. Electro-osmotic drag from the anode to cathode	66. install pressure relief valve		
			14. Regular system checking		
			23. Operator response to high level alarm		
			24. High level Shutdown		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
4.6. Low Level	4.6.1. Potential for gas blow by to the cathode, potential overpressure at the PEM stack, potential for loss mechanical integrity, potential for rupture of vessel, potential release of flammable material, potential fire/explosion.	4.6.1.1. Failure of level controller	14. Regular system checking		8. Consider revising the SOP by implementing the IEC 60079-10-1 that is the international electro technical commission (applied mainly in explosive atmosphere - classification of areas) and EIGA with standard IGC Doc 121/04/E by performing ITPM - Inspection, Testing and preventive measures (applied for mainly Hydrogen transportation pipelines using RAGAGEP document on hydrogen transport and distribution pipelines)
			27. Operator response to low level alarm		
			103. Install a secondary drain to reroute		
			51. Install a pressure relief valve		
		4.6.1.2. Valve is too much open	14. Regular system checking		
			27. Operator response to low level alarm		
			103. Install a secondary drain to reroute		
			51. Install a pressure relief valve		
4.7. High Flow	4.7.1. Difficult to control the heating process, more reactants go to the reactor, incomplete reaction, increase production cost	4.7.1.1. Failure in operation monitor	36. Operator response to high flow alarm		10. Consider revision of FM global with standard 7-91 for Hydrogen with is applied for Hydrogen supply and delivery systems and protections. No hydrogen concentration specified. or OSHA - 29 CFR 1910.103
			14. Regular system checking		
			80. Install high flow detector and alarm		
		4.7.1.2. More flow in one stream than the other	36. Operator response to high flow alarm		
			80. Install high flow detector and alarm		
			14. Regular system checking		
			81. Install control valve		
		4.7.1.3. valve is open too much	105. Gas detection alarm in case of rupture		
			51. Install a pressure relief valve		
			80. Install high flow detector and alarm		
			36. Operator response to high flow alarm		
			14. Regular system checking		
			104. Install secondary backup valve		

4.8. Low Flow	4.8.1. Increase production cost, waste time and energy, low supply of mixture, decrease product concentration, combustion of hot vapors with hazard to and loss of life. Possible formation of explosive	4.8.1.1. Pump malfunction	39. Operator response to low flow alarm		11. Consider vented deflagration panels.
			107. install a secondary pump		
			106. install secondary pipeline		
			14. Regular system checking		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
	mixture in Electrolyzer. Possible ignition, fire/explosion and injury to personnel.		76. Regular pipe cleaning		
		4.8.1.2. Pipe blockage	14. Regular system checking		
			27. Operator response to low level alarm		
			103. Install a secondary drain to reroute		
			51. Install a pressure relief valve		
		4.8.1.3. Pipe leakage	78. Install monitoring system		
			53. Gas detection alarm		
			14. Regular system checking		
			27. Operator response to low level alarm		
			103. Install a secondary drain to reroute		
			51. Install a pressure relief valve		
		4.8.1.4. Loss of Nitrogen flow to anolyte/catholyte tank before startup	125. Low nitrogen shutdown of the Electrolyzer		
			124. backup Nitrogen purge		
			123. Low nitrogen alarm		

4.9. No Flow	4.9.1. No steam, H2 gas supply, waste time, cost and energy, potential fire/explosion due to pressure buildup in the storage tank for H2 gas.	4.9.1.1. Pump failure	81. Install control valve		
			108. Install a secondary backup route		
			43. Operator response to low flow alarm		
			14. Regular system checking		
			73. Install backup pump		
		4.9.1.2. Pump rupture	109. Install alarm		
			81. Install control valve		
			108. Install a secondary backup route		
			43. Operator response to low flow alarm		
			14. Regular system checking		
			73. Install backup pump		
		4.9.1.3. Valve is closed	3. Operator response to high pressure alarm		
			14. Regular system checking		
			30. install a backup valve		

Deviation	Consequence	Cause	Safeguard	L	PHA Recommendation
			110. Install a secondary tank connected to the primary storage tank to vent out the gas to reduce pressure buildup		
4.10. Composition	4.10.1. Potential inflow of O2 to the H2 gas pipeline, Potential fire/ explosion.	4.10.1.1. membrane has reached its end user	105. Gas detection alarm in case of rupture		
			111. Stop operation		
			14. Regular system checking		
4.11. Electrical loss	4.11.1. Loss of feed to the dryer,	4.11.1.1. Pump failure	113. Secondary backup system if AC-DC fails can shift to DC-DC rectifier	3	9. Consider revision of the SOP for source FM Global with standard 5-1 for electrical equipment in Hazardous Equipment in Hazardous (classified) locations (applied mainly for any electrical equipment within an area deemed classified based on HAC study - Hazardous area classification)
			73. Install backup pump		
			14. Regular system checking		
			112. reroute the gas flow		
			111. Stop operation		
		4.11.1.2. Dryer failure	84. automated shutdown to the operation.		
			114. Install secondary column		
4.12. High Cell Voltage	4.12.1. Possible higher diffusion leading to formation of explosive mixture in Electrolyzer, possible ignition, fire/explosion and injury to personnel	4.12.1.1. DC-DC rectifier malfunction	121. High temperature shutdown of the Electrolyzer	3	11. Consider vented deflagration panels.
			120. High temperature alarms at the cell stack.		
4.13. Additional	4.13.1. Possible to send water to the H2 stack. Possible freezing of the H2 vent stack, preventing the H2 to vent when reached. Possible overpressure of the H2 lines with possible ignition fire/explosion and injury to personnel.	4.13.1.1. Water carryover into the H2 vent	132. Set up water drain at H2 vent stack	2	12. Consider setting up heat tracing in the H2 vent line. Consider vented deflagration panels.
			122. Increase the speed of the HVAC system		
4.14. Maintenance	4.14.1. Reduced lifetime of tank may cause damage. Hydrogen leakage to process area leading to fire or explosion.	4.14.1.1. Hydrogen embrittlement Phenomenon	134. Venting system installation	3	13. Replace tank material with stainless steel.
			118. Combustible gas detector		

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