ABSTRACT

Title of Thesis: IDENTIFYING RISK SCENARIOS OF A SOLID OXIDE ELECTROLYSIS FACILITY FOR HYDROGEN PRODUCTION AT NUCLEAR POWER PLANTS

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Solid Oxide Electrolysis (SOE) is a developing technology for the production of clean hydrogen. SOE is a key technology used in a high temperature electrolysis facility, named for the high temperature steam at the inlet of the electrolyzer stack. The required steam temperature of 750 °C, can provided via thermal energy from a Nuclear Power Plant (NPP), which also reduces the electricity required to produce the hydrogen. At present, the U.S. government and industry are researching and testing SOE designs connected to NPPs to enable commercial-scale system hydrogen production at NPPs. Commercial SOE facilities have the potential to produce clean hydrogen at a high efficiency and more flexible operating paradigms for NPPs. The deployment of these systems requires a more robust understanding of the operational hazards of the SOE facility's design. However, to date the published literature has not presented a detailed description of the relevant hazards. This work adds to the growing body of engineering knowledge about hydrogen production facilities by identifying a comprehensive list of failure modes, mechanisms, and consequences. We describe our approach for conducting this analysis and document the SOE system we analyzed. To understand the hazards, a failure modes and effects analysis (FMEA) was conducted on a high temperature electrolysis test facility with a maximum power input of 25 kW and hydrogen production rate of 0.726 kg/hr developed at INL. All identified risk significant scenarios leading to the consequences of membrane degradation, hydrogen and oxygen mixing, hydrogen release, or nitrogen release are discussed. We identified system components that contribute to the most high-risk scenarios and proposed mitigation strategies to reduce these risks. These results were used to develop fault tree structures at a high level of abstraction to identify significant combinations of failures within the system. We created an enumerated list of risk significant scenarios. This research will assist the hydrogen stakeholders to make informed design choices to ensure safety and reliability in the continued development and deployment of SOE technologies. In the future, these results have the potential to be scaled to commercial SOE facility designs. The research provides a starting point for a comprehensive quantitative risk assessment needed to establish the risk-informed regulatory foundations that will ensure the safe and reliable deployment of solid oxide electrolysis coupled to nuclear power plants.

IDENTIFYING RISK SCENARIOS OF A SOLID OXIDE ELECTROLYZER SYSTEM FOR HYDROGEN PRODUCTION AT NUCLEAR POWER PLANTS

by

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List of Abbreviations

BWR	Boiling Water Reactor
DI	Deionized
FMEA	Failure Modes and Effects Analysis
FG	Functional Group
H_2	Hydrogen
HAZOP	Hazard and Operability Analysis
HTGR	High Temperature Gas Reactor
HTEF	High Temperature Electrolysis Facility
HTSE	High Temperature Steam Facility
INL	Idaho National Laboratory
kW	Kilowatt
MMT	Million Metric Ton
NPP	Nuclear Power Plant
O_2	Oxygen
P&ID	Piping and Instrumentation Diagram
PEM	Proton Exchange Membrane
PFD	Process Flow Diagram
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
QRA	Quantitative Risk Assessment
SLPM	Standard Liter per Minute
SOE	Solid Oxide Electrolysis
SOEC	Solid Oxide Electrolysis Cell

Chapter 1: Introduction

1.1 Motivation and Context

Hydrogen technologies stand to play a crucial role in the transition to renewable energy, reduction of greenhouse gas emissions in high-carbon emitting sectors, and achieving net zero emissions by 2050 [1]. Currently, approximately 95% of hydrogen production in the United States relies on steam methane reforming [2]. However, this production method produces a significant amount of carbon dioxide due to the reliance on fossil fuels. With global demand for hydrogen projected to range between 115 and 130 MMT by 2030, the continued development of electrolyzer technology is essential for meeting these needs [3]. Clean hydrogen is produced from water electrolysis coupled with a clean source of electricity. Three types of electrolysis technologies are in various stages of commercialization for use deployment with clean energy sources. Specifically, Solid Oxide Electrolysis (SOE) integrated with nuclear power can efficiently produce clean hydrogen while also supporting numerous sectors' transition away from fossil fuels.

SOE is a key technology for integrating high-temperature steam electrolysis (HTSE) facilities, also known as high-temperature electrolysis facilities (HTEF), with clean energy sources. The required steam temperature of 750 °C, can provided via thermal energy from a Nuclear Power Plant (NPP), which also reduces the electricity required to produce the hydrogen [4]. Incorporating SOE technology with NPPs is advantageous because the HTEF effectively utilizes excess thermal and electrical energy generated by an NPP to produce high-purity hydrogen. Additionally, during periods of high electricity demand, a reversible solid oxide electrolyzer operated in fuel cell mode can use hydrogen as a fuel to produce electricity for the power grid [5]. SOE technologies offer favorable thermodynamics and reaction kinetics, leading to a higher conversion efficiency and reduced electricity demand for hydrogen production when compared to other electrolyzer technologies [2, 6, 7]. Conversely, Proton Exchange Membrane and Alkaline electrolyzers operate at a lower temperature and require more electrical energy input to split liquid water into hydrogen and oxygen. SOE is a highly efficient technology for meeting projected demands, especially with research efforts driving development towards mega-watt and giga-watt capacities.

The U.S Department of Energy and Idaho National Laboratory (INL) are actively researching and testing SOE systems in anticipation of commercial-scale system developments at NPPs [5, 8–10]. SOE facilities have the potential to produce clean hydrogen at a high efficiency high efficiency and more flexible operating paradigms for NPPs. However, nuclear-integrated hydrogen plants are complex engineered systems that have not been fully analyzed from a risk assessment perspective. Research on SOE technology has yet to address one of the fundamental questions of risk analysis: what can go wrong? To date, most electrolyzer risk and reliability research has focused narrowly on identifying materials that enhance the performance and durability of the electrolyzer stack, to extend the lifespan and further increase efficiency [11–13]. However, while the electrolyzer stack is a critical component of the electrolyzer system, the full-scale electrolyzer system includes a balance of plant, which includes all of the auxiliary equipment that supplies process medium to the stack, that is often neglected. The balance of plant is responsible for ensuring the electrolyzer stack's ability to safely and reliably produce high-purity hydrogen [14, 15]. Moreover, the design of the balance of plant introduces unique components and operating conditions that may result in complex failure events, which have not been fully addressed.

This thesis aims to identify and characterize relevant component failure modes, mechanisms, and risk scenarios for SOE. We start by conducting a failure modes and effects analysis (FMEA) following a standardized process on a detailed, publicly available SOE facility design. Furthermore, we accounted for the co-location of an SOE facility with an NPP by including risk scenarios that could arise outside of normal operation. For example, NPPs may provide variable thermal and electrical energy to SOE facilities, resulting in various operational states, including hot standby, startup, and shutdown. The risk scenarios associated with these operational states serve as a basis for understanding the potential interactions between an SOE facility and an NPP. The results of the FMEA are leveraged in developing fault tree structures at a high level of abstraction to identify combinations of critical component failures and discuss the key safety controls within the system. By identifying risk scenarios and constructing high-level fault tree logic models, we have built both critical insights for early deployment decisions and the foundation for a comprehensive quantitative risk assessment (QRA) of an SOE facility. In the future, these results have the potential to be scaled to commercial SOE facility designs and establish the risk-informed regulatory foundations that will ensure the safe and reliable deployment of SOE technologies.

1.2 Objective

The objective of this research is to identify component failure modes and risk scenarios for a solid oxide electrolyzer to inform hydrogen system development and provide the foundations for a future QRA by conducting and documenting a comprehensive FMEA on an SOE facility coupled to an NPP. To achieve this goal, the work was divided into four separate tasks as follows:

1. Document the current state of the art of Solid Oxide Electrolysis technology and risk modeling by conducting a literature review
2. Establish a detailed SOE facility based on publicly available information
3. Identify component failure modes and risk scenarios for an SOE by conducting a comprehensive FMEA
4. Identify significant areas of failure by developing fault trees at a high level of abstraction

The tasks, results, and impact of the work are summarized in Figure 1.1.

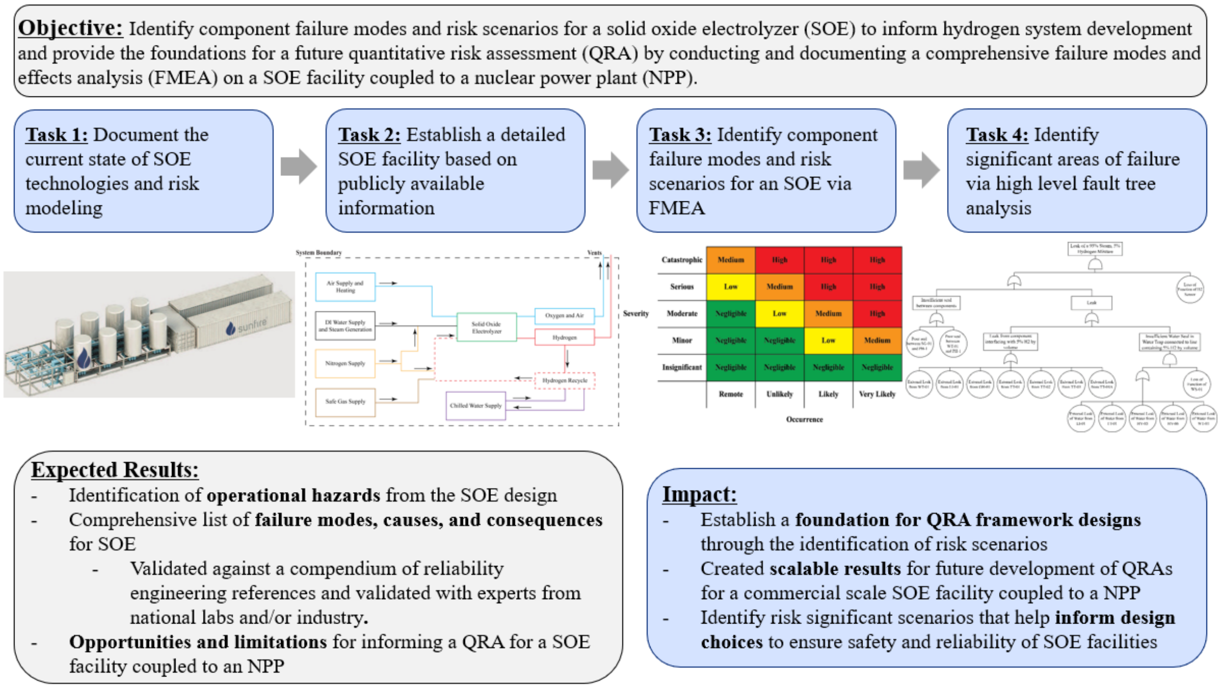

Figure 1.1: Thesis task breakdown

1.3 Approach

1.3.1 Task 1: Document the current state of the art of Solid Oxide Electrolysis technology and risk modeling by conducting a literature review

For Task 1, we conducted a literature review on the current state of knowledge related to SOE, risk modeling, and system integration of SOE facilities with NPPs. A thorough review of SOE technology aided in gaining a deeper understanding of the complexity and unique aspects of the system. Reports published by INL provided the basis for understanding how the excess thermal energy can be extracted from an NPP for use in co-located facilities, such as HTEFs [9, 10]. We built upon the literature review conducted by Al Douri and Groth [15] that identified research opportunities in electrolysis risk and reliability. From the expanded literature review, we learned that there are a limited number of analyses on SOE risk modeling. We also identified that designs for hydrogen-nuclear integration thus far have only proposed heat extraction systems, which reside on the nuclear island, for transferring the necessary thermal energy to the hydrogen facility. We identified current research gaps and established our approach to address the specific gap of a lack of well documented insights from a comprehensive and rigorous risk scenario identification process to inform QRA.

1.3.2 Task 2: Establish a detailed Solid Oxide Electrolysis facility based on publicly available information gathered in the literature review

In Task 2, we synthesized the knowledge acquired in Task 1 to adapt a publicly available SOE design and conduct our analysis. A diagram of a 25-kW input power test-bed design published by O'Brien et al. [16] was selected because the design provided the level of detail necessary for the analysis. Additionally, O'Brien et al. [16] provided a detailed system description, nominal operating conditions for the 25-kW testing, and photos of the system configuration which aided in our understanding of the system. We modified the original design to include necessary sensors that would be present in the safety and control system of large-scale facilities. We defined a new system boundary in an effort to account for all of the components that would be present in a containerized SOE facility. Next, we decomposed the system into functional groups based on the primary purpose of each component to better visualize the system's process flow. As a result, we established a 25 kW SOE facility design with all of the necessary information to inform QRA and aid in the scalability of key insights to commercial scale system designs.

1.3.3 Task 3: Identify component failure modes and risk scenarios for a Solid Oxide Electrolyzer facility by conducting and documenting a comprehensive FMEA

Task 3 consists of four sub-tasks: assembling the FMEA team, conducting the analysis, synthesizing and validating the results. We assembled the FMEA team using five experts whose combined knowledge included hydrogen system safety and low temperature water electrolysis system risk and reliability. We assembled the knowledge base, we developed a system reference guide to outline the functional group system description, the risk ranking, and a taxonomy for the failure modes, mechanisms, and consequences. In the analysis, the consequences we considered were hydrogen release, nitrogen release, hydrogen and oxygen mixing, and membrane degradation leading to significant system downtime. We selected these consequences due to the risks they can potentially pose to facility personnel, user and general population safety. We further refined the risk scenarios by collaborating with the experts who work directly with the test-bed SOE facility, from INL, such that we could produce detailed scenarios that reflect normal system operations. We synthesized the results to document the 65 critical risk scenarios that could be utilized by engineers and scientists as they continue to iterate on the design of SOE facilities coupled to NPPs.

1.3.4 Task 4: Identify significant areas of failure within the system via high level fault tree analysis

In Task 4, we establish the high-level failure understanding and logic of the analyzed SOE system by developing fault tree logic models at a high level of abstraction. Each potential consequence of interest, such as hydrogen release, hydrogen and oxygen mixing, membrane degradation, or nitrogen release, became a top event in a fault tree logic model. We leveraged the FMEA results to categorize component failures by consequence type. Then, Boolean logic was employed to model how various component interactions led to a specific top event. Additionally, the fault tree logic models visually displayed combinations of critical component failures and highlighted the significant safety controls that are necessary to mitigate the occurrence of undesired system failures. These results provided a basis for subsequent quantification of the fault tree structures in an effort to prioritize key safety measures and the reliability of specific areas of the system to inform future iterations of SOE facility designs.

1.4 Technical Contributions

Compared to previous work, the key technical contributions of this work are:

- **Contribution 1: SOE Facility Failure Modes and Causes**. The development of a comprehensive set of relevant failure modes, for over 80 components of an SOE facility spanning water supply and steam generation, electrolysis stack, oxygen processing and production, hydrogen production and recycle and additional critical functional groups. Through the FMEA process, we also qualitatively evaluated the likelihood of occurrence and severity of each component failure mode to classify the risk posed to the overall SOE system. For each component and its failure modes, we provide the number of high and medium risk-scenarios.

- **Contribution 2: Critical Risk Scenarios List for an SOE Facility**. We synthesize a list of the 65 most critical risk scenarios from over 650 risk scenarios we identified. These critical risk scenarios apply to an SOE facility both during normal operation and outside of normal operation. We have provided a readily available record of critical scenarios, which are fully discussed and elaborated upon within the FMEA documentation.

- **Contribution 3: Basis for QRA for an SOE Facility**. We created system failure understanding and logic that provide the foundation for QRAs needed to establish the regulatory foundations to ensure the safe and reliable deployment of solid oxide electrolysis. We developed fault trees to identify combinations of critical component failures and visually display the relevant component failure modes that result in specific undesired system failures which can pose undue risk as a basis for subsequent quantification in QRA.

In all, we were able to contribute to the overall state of knowledge of SOE system failure in an effort to support the roll out of early stage deployments and lay the foundations for informing future design and siting recommendations with QRA.

1.5 Thesis Structure

The remainder of this document is structured as follows. Chapter 2 contains background information on SOE technology and a literature review on the current efforts in SOE risk modeling and hydrogen-nuclear integration. Then, Chapter 3 provides a piping and instrumentation diagram (P&ID) and complete system description, including operating conditions, for the 25-kW test-bed design used in our analysis. Chapter 4 presents the risk scenarios identified via a comprehensive FMEA. Then, the results of the FMEA are leveraged to develop fault trees at a high level of abstraction. The high-level failure logic for our system is also presented in Chapter 5. Lastly, Chapter 6 concludes with a brief summary of the project, its impact, a list of completed and expected publications and opportunities to extend the work further.

Chapter 2: Background

2.1 Current Challenges of Solid Oxide Electrolysis

SOE is an emerging technology in the research and development phase, aiming to enable large-scale hydrogen production. High degradation rates due to the intrinsic properties of the electrolyzer stack impact the performance and efficiency over time. Multiple studies have investigated and summarized the impacts of degradation on electrolyzer stack performance [17–20]. However, component failures within the balance of plant have the potential to cause or accelerate degradation that could lead to irreparable damage to the electrolyzer stack. A limited number of available works briefly discuss how failures in the overall facility negatively impacted the electrolyzer stack. Ghezel-Ayagh [21] noted that steam starvation due to faulty control of the humidifier resulted in severe irreparable damage to the electrolyzer. Aicart et al. [22] also briefly discussed the series of events, including human error, and controlled and uncontrolled facility shutdowns that resulted in irreversible degradation of the electrolyzer stack. Mougin et al. [23] also noted that the system underwent several unplanned events, one of which was caused by failures of the steam supply. However, even though these events impact the behavior and temperature evolution of the stack, they were not considered in the degradation analysis. Lang et al. [24] focused on the long-term behavior of a solid oxide electrolyzer in electrolysis and fuel cell operation modes. They mention that the stack experienced 3 startup and shutdown cycles due to facility issues, however in their analysis they did not consider the impact of these events on stack performance. Although failure events within the facility were the cause of pronounced electrolyzer stack degradation and failure, current research efforts remain focused on improving the stack materials and design.

Research efforts are evaluating the electrochemical performance and conducting post-mortem analyses of electrolyzer stacks to improve current designs. Frey et al. [25] conducted a 20,000-hour test on a two-layer solid oxide electrolyzer stack at 800 °C and -0.5 A/cm^2. Through electrochemical characterization, they concluded that increasing ohmic resistance was the leading degradation mechanism. Visual inspection after stack dissection revealed signs of burning in the second layer of the stack and partial delamination of the air electrode due to chromium poisoning from the uncoated metal foil at the ends of the cell. In practical applications, the damage and delamination lead to significant decreases in stack efficiency and would ultimately require stack replacement. While there are valuable insights from studying a two-layer SOE stack, practical applications require analysis and testing of larger electrolyzer stacks and the parallel coupling of multiple stacks to achieve giga-watt capacities. An increasing number of cells introduces new challenges for electrolyzer stack reliability, including the homogeneity of cell performance and the durability of the interconnects.

Aicart et al. have published several studies conducting performance and post-mortem analyses of solid oxide electrolyzers with 25 cells, 30 cells, and four-stack modules. In the analysis of the 25-cell stack, they investigated the effect of 6,700 hours of normal operation on the cells, seals, and interconnects to assess durability [26]. The results indicated that the fuel electrode experienced nickel depletion, which resulted in significant performance loss. In their investigation of the 30-cell stack, two different electrolyzer stacks were tested under thermoneutral conditions, with temperatures ranging from 780 °C to 850 °C [22]. The first stack featured multiple cell variants and had a manufacturing defect that caused an internal gas leak early in testing. The subsequent mixing of gases resulted in the combustion of hydrogen and oxygen, which increased individual cell degradation and resulted in a stack lifespan of 6,800 hours, respectively. During the post-mortem analysis, the over-temperature caused by the combustion was identified as the likely cause of cell fractures in two other stack layers. The second stack, which only used the best cell variants, exhibited a decreasing degradation rate, which resulted in a stack lifespan of approximately 11,500 hours. Aicart et al. [27] explored the performance of a reversible large stack solid oxide electrolysis module to determine the feasibility of further scaling up SOE technologies. Throughout the experiment, the reversible module demonstrated low performance dispersion and responded well to a fast current ramp rate. Collectively, this body of research provides valuable insights into the performance and longevity of SOE stacks and modules, reinforcing the feasibility of commercializing this technology for integration with clean sources of electricity. However, despite including process flow diagrams (PFDs) and test setup descriptions, their work falls short of providing a sufficient level of depth on the system necessary to conduct a QRA. Additionally, the decreases in performance identified in these studies are due to inherent features of the electrolyzer stacks, including quality and manufacturing defects. However, they do not consider how component failures within the balance of plant can induce these same or worse effects on the stack performance.

2.2 Current State of SOE Risk Modeling

Al-Douri and Groth [15] conducted a comprehensive literature review on the current state of risk and reliability analysis for electrolysis technologies. To date, existing research has focused on Proton Exchange Membrane (PEM) and Alkaline water electrolysis due to their broader commercial deployment. In their review, Al-Douri and Groth [15] identified only three publications addressing risk and reliability for SOEs. Bao et al. [28] developed a multi-physics model to evaluate the electrochemical performance and structural reliability of SOECs in an effort to optimize SOEC designs for hydrogen production without the need for significant testing. The structural reliability analysis on a large area planar SOEC revealed a low risk of rupture failure probability with minor localized potential damage under the chosen operating conditions. While it is important to characterize how normal operating conditions impact a SOEC's structural integrity, they did not consider the impact of balance of plant component failures on operating conditions or the subsequent effects on SOEC operation. In another study, Cipolleta et al. [29] carried out an inherent safety assessment using process flow diagrams (PFDs) of alkaline, PEM, and reversible SOECs, each with a hydrogen production rate of 60.8 kg/hr. They considered three loss of containment scenarios, utilized event trees to identify potential release accident scenarios, and calculated two inherent safety indices. They concluded that SOE technology was the least inherently safe option due to its high operating temperature and increased compression requirements for hydrogen storage. However, they only considered hydrogen release, which highlights the need to study other consequences, including membrane degradation and hydrogen and oxygen mixing. Similarly, Glover et al. [30] performed a consequence analysis using a PFD of a large-scale HTEF. The study investigated the risk posed by an HTEF coupled with an NPP at a separation distance of 1 km. They briefly discussed the methodology of the hazard and operability analysis (HAZOP) used to identify leakage scenarios and provided a list of 15 operational state scenarios for various system sections. The full rupture consequence did not impact the fragility of target areas of the NPP, which led them to conclude that the separation distance can be safely reduced from 1 km. Each of these three studies contributes to the characterization of operational hazards of SOE systems under normal operating conditions. However, due to limited system detail and lack of in-depth discussion of the identified failure scenarios in these analyses, they cannot support QRA efforts for SOE systems. QRA needs a comprehensive hazard identification of an SOE facility coupled with an NPP as a starting point.

2.3 Current State of Nuclear-SOE Integration

INL has developed designs for integrating SOE with NPPs. Westover et al. [10] developed conceptual designs for the integration with 100 MWe and 500 MWe high-temperature electrolysis plants linked to pressurized water reactors (PWRs). They selected a 4-loop Westinghouse PWR design, representative of the current NPP fleet in the USA, to create the preliminary integration design. Their work includes design details for the steam extraction, reboiler, and electrical systems necessary for the NPP to supply thermal and electrical power to the hydrogen production facility. However, they provide limited detail on the components and safety and control systems required to span the separation distance between the nuclear island and the high-temperature electrolysis facility. Without this design information, characterizing the critical component failure modes and postulating the resulting risk scenarios is a significant challenge.

As the next generation of reactors is being developed by companies like X-Energy and

NuScale, Novotny et al. [9] have established preliminary P&IDs of advanced reactors coupled to high-temperature steam electrolysis facilities and oil refineries. These simplified P&IDs outline the heat extraction system and describe how deionized water is preheated using steam from the reactor. They also considered thermodynamic and electrical balance to justify the configurations and proposed the necessary adjustments to the nominal operation control scheme on the nuclear side. Through various projects, INL laid the groundwork for designing heat extraction systems that will assist in the deployment of SOE technologies at NPPs. Heat extraction is critical to coupling SOE facilities to NPPs because nuclear steam cannot be used directly in electrolysis. Deionized water is required to produce high-purity hydrogen and ensure minimal degradation of the electrolysis facility components. Additionally, Agbaje et al. [31] investigated the design and operation of heat extraction systems for coupling boiling water reactors (BWRs) to high temperature electrolysis facilities. However, the lack of detail on the exact components needed to connect the heat extraction system to the SOE facility poses a challenge to characterizing the risks imposed by either system on the other.

Additionally, Vedros et al. [8] expanded their initial hazard assessment and probabilistic risk assessment (PRA), found in [32], to incorporate a heat extraction system and direct electrical connection to support co-location. Their FMEA was conducted at the system level, focusing exclusively on the hazards presented to the NPP. The subject matter experts identified hydrogen detonation at the HTEF as one of the primary hazards affecting the NPP. The PRA used generic PWR and BWR models, factoring in the thermal and electrical integration with HTEFs. The PRA results for co-location indicated that the core damage frequency increased minimally, with the largest increase being 7.7%. However, their work takes a conservative system-level approach by identifying a limited number of the high-consequence events that would lead to NPP damage.

Focusing exclusively on the effects on NPP operation results in an analysis that only considers one direction of scenario evolution that provides insights into a subset of the overall risks. By considering only the effect of various hydrogen detonations, steam pipe ruptures, and stacked SOE modules falling over, their analysis excludes both how a transient event in the NPP could negatively impact the SOE facility and how the balance of plant equipment can cause critical SOE system failures that could evolve to pose undue risk on the NPP. Therefore, it becomes crucial to characterize the failure modes of an SOE facility at the component level to help inform design choices and ensure the safe and reliable deployment of SOE technology.

2.4 Knowledge Gaps, Opportunities for Research, and Approach

The literature review examined ongoing efforts in SOE technology development, risk modeling, and integration of SOE facilities with NPPs. Groth et al. [33] highlighted that four of the ten barriers to wider adoption of hydrogen technologies, as identified by a U.S Department of Energy survey, are closely linked to the concerns regarding the safe and reliable deployment of electrolysis technology. The International Association for Hydrogen Safety identified several opportunities for research to advance the state of hydrogen safety, including the need for electrolyzer risk analysis and the need for QRAs of electrolysis technology coupled to NPPs. The Hydrogen Systems Risk and Reliability Workshop identified electrolysis risk analyses with emphasis on the balance of plant as a key way to ensure reliable up-time of mega-watt capacity facilities [14]. Al-Douri and Groth [15] summarized the extent of the knowledge gaps in water electrolysis risk and reliability. The first crucial gap involves the lack of dissemination of detailed SOE system designs. As the literature review highlighted, simplified PFDs including most of the major components are available; however, they lack sufficient detail on the temperature and pressure conditions, flow rates, and other key information required to inform a comprehensive QRA. Risk analysis are highly design specific, therefore detailed design information is essential to the scalability of early QRA insights to commercial system. Additionally, some studies conducted analysis solely on an electrolyzer cell or stack; however, no studies conducted an analysis on the whole SOE system which includes the balance of plant. This lack of system-level reliability modeling was another critical gap identified by Al-Douri and Groth [15]. Evaluating electrolysis reliability at the system level requires the consideration of the balance of plant to fully understand how an undesired system failure is initiated by a component failure within the balance of plant.

Our approach to address these gaps is described as follows and further elaborated upon in the following chapters. We began by reviewing and synthesizing the literature to select an SOE facility design with a sufficient level of detail in order to conduct our analysis. Using the P&ID provided in [16], we defined a new system boundary, all necessary safety and control systems and complied the relevant system operating conditions. We established a 25 kW SOE facility design with all of the necessary information to inform future QRA and aid in the scalability of key insights to commercial system designs. We rigorously documented our approach to conduct the FMEA by following the IEC 60812 (2018) FMEA standard [34], guidance from Modarres and Groth [35] and Wismer et al. [36]. Lastly, we leveraged the results of the FMEA to create fault tree structures which describe the system failure understanding and logic at a high level of abstraction by following guidelines from Modarres and Groth [35] and the NUREG fault tree handbook [37]. We aim to address the identified gaps by providing a comprehensive set of failure modes and causes, a list of critical risk scenarios and a basis for QRA for an SOE facility.

Chapter 3: System Description

3.1 Definition of Solid Oxide Electrolysis

During high temperature electrolysis, an furnace is used to maintain the proper operating temperature of an SOE stack. The balance of plant supplies a mixture of steam and hydrogen into the cathode compartment of the stack. The steam is split into hydrogen and oxygen ions via the hydrogen evolution reaction at the boundary between the electrolyte and hydrogen electrode [13]. The presence of hydrogen at the inlet is needed to maintain the proper reducing conditions in an effort to minimize the occurrence of oxidation in the cathode compartment of the stack [16]. The produced hydrogen diffuses back into the gas flow and continues into the rest of the electrolyzer system for cooling, drying, compression and storage. Meanwhile, oxygen ions travel across the electrolyte to the anode, where they react to form oxygen gas and electrons via the oxygen evolution reaction [2, 13]. The balance of plant then supplies air to remove the oxygen gas from the anode of electrolyzer stack. The mixture of air and oxygen gas then travels to the rest of the electrolyzer system either for storage or venting.

An SOE stack is made up multiple Solid Oxide Electrolysis Cells (SOECs), which are connected in series. SOECs are classified based on their geometry and the type of ions they transport within the electrolyte [12]. SOECs can have either a tubular or planer design and one of three flow field patterns. Norman et al. [19] identify parallel, counter, and cross-flow as the most common patterns. Planer SOECs are more prevalent today due to their simpler geometry, which reduces manufacturing costs. Furthermore, SOECs are categorized according to the type of electrolyte used in the cell. The two main types of electrolytes are those that conduct oxygen ions or hydrogen protons. Oxygen-ion conducting cells, known as O-SOECs, are the more widely used because the oxygen ions have shown higher migration rates and better performance under higher temperatures [12]. The design introduced in this section uses an oxygen-ion conducting SOE stack with a parallel flow pattern. In contrast, proton-conducting electrolytes, known as H-SOECs, are suitable for lower-temperature operation. However, no demonstration systems or industrial-scale applications have been reported for H-SOECs. Herein, we refer to O-SOECs as SOECs in the discussion.

Planar SOECs have a sandwich structure comprised of a cathode electrode, electrolyte, and anode electrode. A barrier layer is often introduced between the electrolyte and the anode electrode to account for differing thermal expansion coefficients and to prevent unwanted reactions at the interface. The state-of-the-art configuration typically consists of a nickel-based cermet cathode electrode, yttria-stabilized zirconia (YSZ) electrolyte, $Ce_{1-x}Gd_xO_{2-\delta}$ (CGO) barrier layer and an $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ (LSCF) anode electrode [13]. While the exact size of each of these layers depends on the support configuration of the cell, the operation of the cell is unchanged.

The configuration of a single planar SOEC is shown in Figure 3.1. A set of SOECs is connected in series to form a solid oxide electrolyzer stack. A set of electrolyzer stacks can then be connected in parallel for large capacity industrial applications. The overall SOE system gains its name from the electrolyzer stack. The electrolyzer stack is responsible for reducing the steam into hydrogen and oxygen ions, but it cannot function without the balance of plant which supplies the process medium and electrical power. All of the components that make up the balance of plant ensure that the electrolyzer is operating within the proper parameters to ensure a long and safe system life. Herein, we use the term electrolyzer to refer to the stack, while SOE system or facility refers to the balance of plant and the stack.

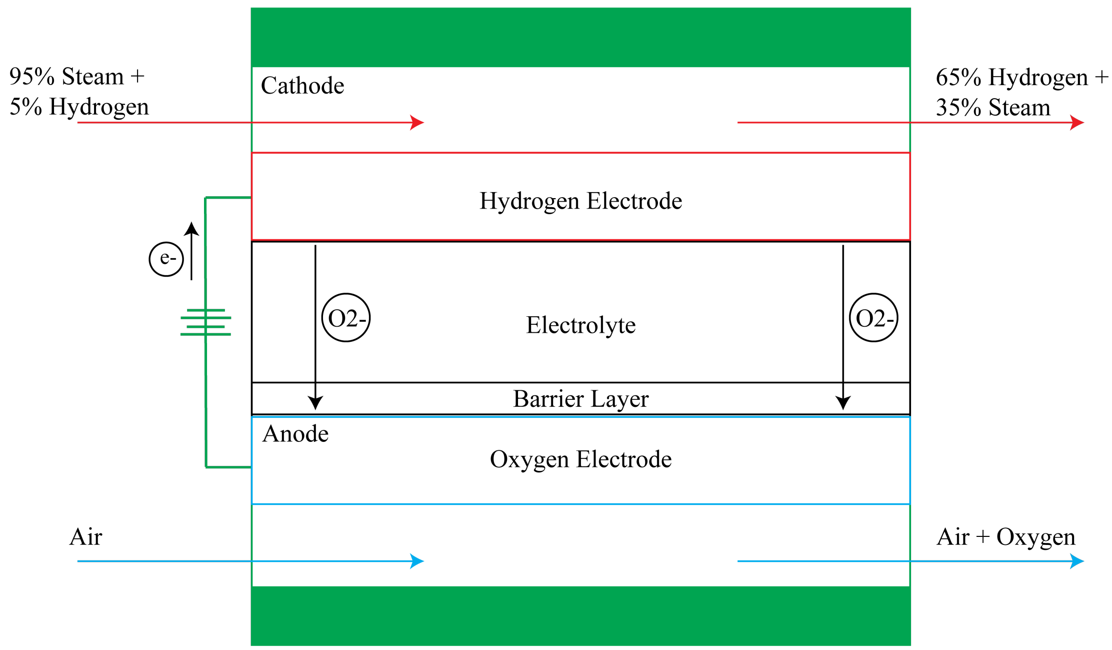

Figure 3.1: Example Planer SOE Cell Configuration

3.2 Design of a Solid Oxide Electrolysis Facility

The design used in this analysis is a SOE test facility with 25 kW maximum input power and hydrogen production rate of 0.726 kg/hr from O'Brien et al. [16]. INL has developed the facility to evaluate the performance of SOE stacks from various industry partners, including Bloom and OxEon. The facility is located inside one of their laboratory buildings, with the SOE stack and balance of plant components housed within a ventilated enclosure, as shown in Figure 3.2. The P&ID used in our analysis, which is an adapted version of the original diagram from

O'Brien et al. [16], is shown in Figure 3.3. To adapt the original design, we added components that were deemed necessary for safe and reliable system operation. Specifically, a flood sensor, hydrogen in air detection sensor, and an air monitoring sensor that would likely be present in a large-scale SOE system. We defined our system boundary to align more with a containerized SOE facility in an effort to produce risk scenarios that can be translated to larger capacity systems. In our adapted design, there are a total of 116 components, that we categorized into seven functional groups. The definitions of abbreviations and brief descriptions of components are given in Table 3.1.

(a) Overview of the facility

(b) Interior of the facility

Figure 3.2: 25 kW SOE test facility at INL [16]

3.2.1 System Process Description

The process flow for the system shown in Figure 3.3 is described as follows. A high-purity DI water supply system provides purified water to the steam generator, which produces steam at 400 °C and ambient pressure. For H_2 production, a mixture of steam (95%) and hydrogen (5%), by volume, is introduced to the cathode side of the high-temperature electrolyzer cells. Nitrogen is included in the cathode inlet gas mixtures sometimes to provide independent variation

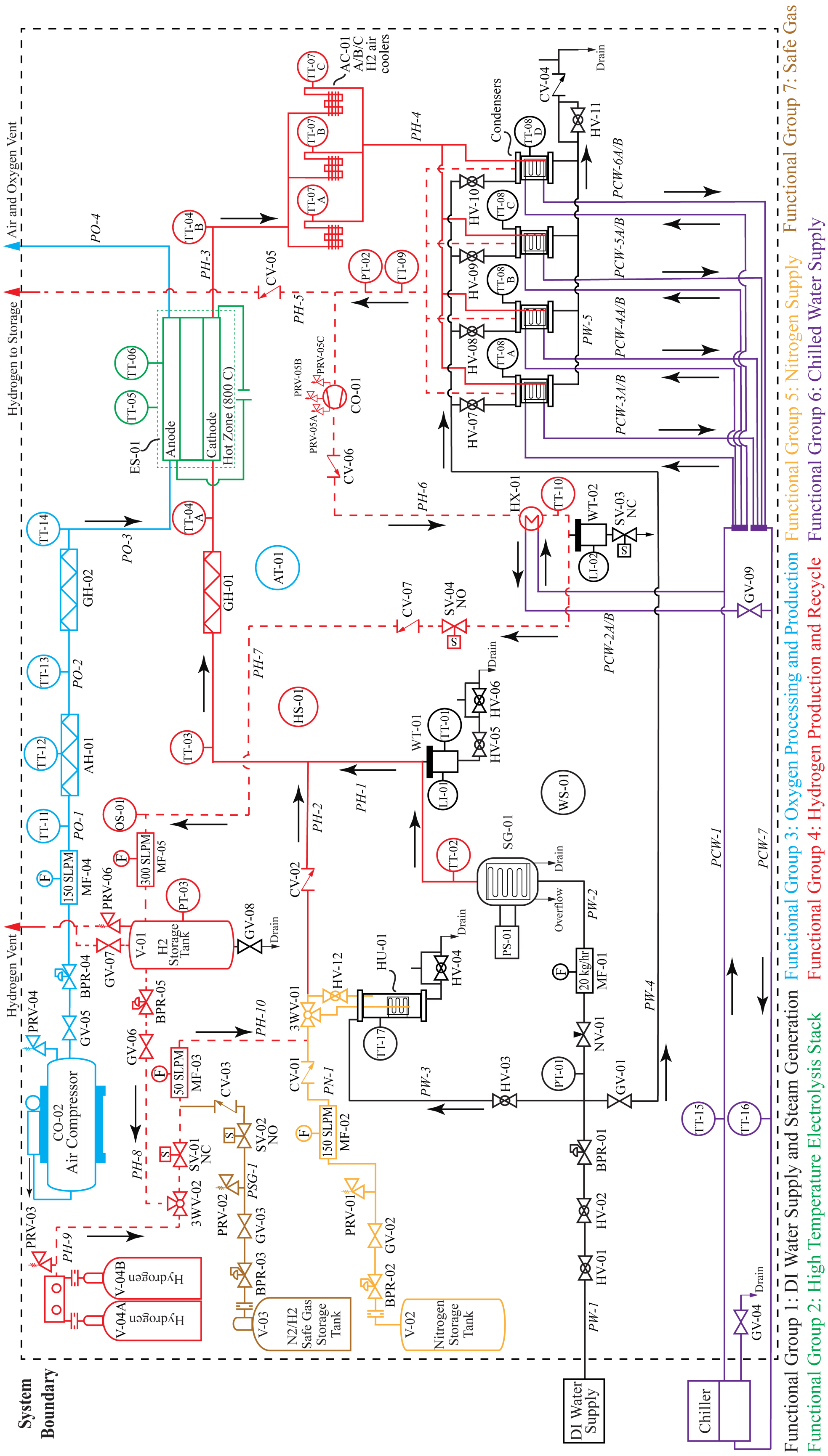

Figure 3.3: SOE Facility P&ID adapted from O'Brien et al. [16]

ID	Name	Description
AC	Air Cooler	Finned-tube heat exchanger
AH	Air Heater	In line heater that heats process air to 400 °C
AT	Air Quality Sensor	Detects nitrogen gas inside the facility
BPR	Back Pressure Regulator	Valve that maintains set upstream process medium pressure
CO	Compressor	Pressurizes process medium
CV	Check Valve	Valve that prevents backflow of process medium
ES	Electrolyzer Stack	Splits steam into hydrogen and oxygen
GH	Guard Heater	In line heater to increase temperature of process medium
GV	Gate Valve	Valve that is either fully open or fully closed
HS	Hydrogen Sensor	Detects hydrogen gas inside the facility
HU	Humidifier	Mixes water vapor with nitrogen
HV	Hand Valve	Manually operated valve
HX	Heat Exchanger	Counter flow heat exchanger to further cool hydrogen gas
LI	Level Indicator	Water level indicator
MF	Mass Flow Controller	Control device that automatically regulates the flow of a process medium
NV	Needle Valve	Valve that restricts flow of process medium
OS	Oxygen Sensor	Detects oxygen gas inside the facility
PCW	Chilled Water Pipe	Chilled water Functional Group piping
PH	Hydrogen Pipe	Hydrogen Functional Group piping
PN	Nitrogen Pipe	Nitrogen Functional Group piping
PO	Oxygen Pipe	Air and Oxygen Functional Group piping
PT	Pressure Transducer	Detects abnormal pressure in piping or components
PRV	Pressure Relief Valve	Valve that prevents overpressure of process medium
PS	Power Supply	Provides electrical energy to components
PSG	Safe Gas Pipe	Safe Gas Functional Group piping
PW	DI Water Pipe	DI Water Supply and Steam Generation Functional Group piping
SG	Steam Generator	Induction heating, atmospheric pressure steam generator
SV	Solenoid Valve	Electronically controlled valve
TT	Temperature Transducer	Detects abnormal temperature in piping or components
V	Vessel	Storage vessel for process medium
WS	Water Flood Sensor	Detects external leakage of water
WT	Water Trap	Collects excess water
3WV	3 Way Valve	Control the path of process medium by allowing only two of three paths to open at once

Table 3.1: Component IDs for the SOE Facility

of partial pressures of the other process gases while operating at a total pressure equal to ambient. However, nitrogen is primarily used as a purge gas to purge air and O_2 out of the stacks and H_2 from the exhaust line. During operation, H_2 flow is required at the stack inlet to maintain reducing conditions on the nickel cermet SOEC cathodes and reduce the migrate of nickel across the cathode. Upon startup, inlet H_2 is supplied from a compressed gas cylinder. For long-term operations, recycled electrolytically-produced H_2 is supplied from a recycle system including condensers, compressors, a high-pressure heat exchanger, and H_2 storage tank. Produced O_2 is mixed with preheated compressed air on the anode side of the stacks and vented from the system. During an alarm condition, a safe gas mixture of nitrogen (96.04%) and hydrogen (3.96%) is supplied to the SOEC cathode to prevent oxidation damage. To better visualize the way in which process mediums travel across the P&ID, we developed Figure 3.4.

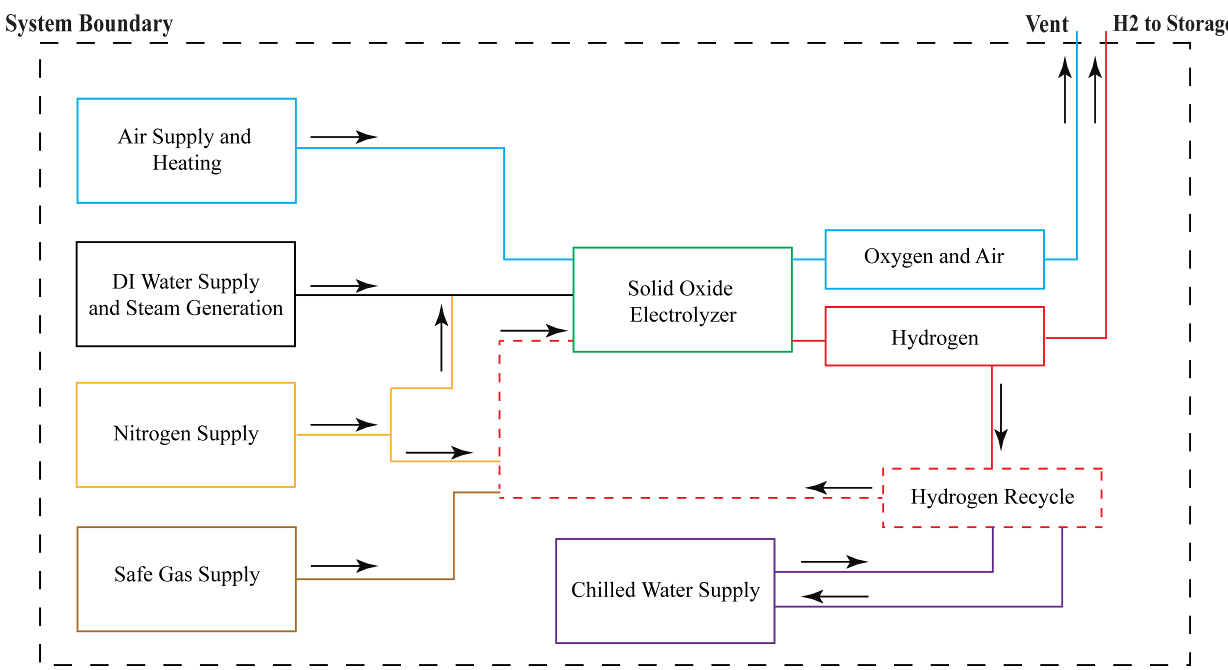

Figure 3.4: Simplified PFD for SOE Facility

Components were grouped into one of 7 functional groups based on a careful analysis of their function within the system. Functional Group 1 is DI water supply and steam generation, which provides purified water to the steam generator that produces steam at ambient pressure to 400 °C. Functional Group 2 is high temperature electrolysis. The components include the SOE stack, the furnace and DC power supply. Functional Group 3 is oxygen processing and production, which provides preheated air at 400 °C that is used to sweep out oxygen on the anode side of the electrolyzer. The components include the sweep gas preheat system and ventilation piping directly after the electrolyzer stack. Functional Group 4 is hydrogen production and recycle. Hydrogen production transports produced hydrogen to be vented, while hydrogen recycle transports some produced hydrogen to be cooled, compressed and stored for use in the inlet to the electrolyzer. Functional Group 5 is nitrogen, which is used for maintenance and start up activities to flush the system and also to provide independent pressure variation of partial pressures of other process gases. Functional Group 6 is chilled water, which provides recirculated water used to cool produced hydrogen prior to compression and storage. Lastly, Functional Group 7 is safe gas, which is used during alarm conditions to continue the flow of nitrogen and hydrogen through the cathode of the electrolyzer to prevent oxidation damage.

3.2.2 System Operating Conditions

In order the conduct a comprehensive analysis, the system operating conditions are required. O'Brien et al. [16] published a list of nominal operating conditions for the full 25 kW test setup at INL. Jorgensen [38] published a design review on INL's proposed SOE test layouts, which included the 25-kW test bed design and operating pressure and temperature information for the system. Table 3.2 presents the complied operating information from both sources, in addition to information we received directly from our collaboration with INL. The operating conditions that are absent from the table represent values that were not published or able to be given directly by INL.

System Area	**Operating Pressure**	**Operating Temperature**	**Flow rate**
PW-1 through PW-2	40 psig	20 °C	10.8 kg/hr
PH-1	< 1 psig	400 °C	24.9 SLPM H2 and 224 SLPM Steam
PO-1 through PO-2	< 1 psig	400 °C	160 SLPM
PO-4	< 0.5 psig	800 °C	227 SLPM
PH-3	< 0.5 psig	800 °C	159 SLPM H2 and 89.6 SLPM Steam
PH-4	< 0.5 psig	150 °C	-
PH-5	< 0.5 psig	15 °C - 20 °C	-
PSG-1	40 psig	-	-
PN-1	40 psig	-	150 SLPM
Water Cooling	-	5 °C	-

Table 3.2: SOE facility operating conditions

3.3 Hydrogen Production at a Nuclear Power Plant

SOE technology demonstrates the highest efficiency and the ability to produce high-purity hydrogen. It operates at temperatures above 600 °C, making it an excellent candidate for integration with NPPs, specifically high-temperature gas reactors (HGTRs). Kupecki et al. [39] conducted a study on the qualitative and quantitative assessment of the efficiency of an HTGR coupled to an SOE system. The authors considered when the HGTR supplied only high-temperature steam and the HGTR supplied electricity and high-temperature steam to the SOE facility. The authors concluded that the highest electrical efficiency, 89.11%, is achieved in the second scenario. However, the higher hydrogen production rate is achieved when the HGTR only supplies high-temperature steam. These results substantiate that SOE is a suitable candidate for integration with advanced reactors such as HTGRs.

There are two proposed methods of integrating SOE facilities with NPPs. In the first method, the SOE facility includes a stand-alone electrical energy source, and the NPP supplies only high-temperature steam to the SOE facility. However, an NPP's high temperature steam cannot be directly fed into a solid oxide electrolyzer stack. The steam in an NPP's nominal balance of plant has strict chemical control due to the potential for increased levels of radiation from possible steam generator leaks and proximity to primary nuclear coolant [9]. Specifically, to reduce the possibility of tritium migration outside of the nuclear fence, a heat exchanger system is required to extract the necessary thermal energy from the NPP for use in an SOE system. Additionally, a solid oxide electrolyzer requires DI water to achieve the highest possible efficiencies and preserve the integrity of the stack. Water containing minerals and other ions can cause adverse side reactions that could potentially damage the electrolyzer stack and reduce facility uptime. Therefore, the SOE facility will require its own water supply that will be heated to temperature by way of excess nuclear process heat. In addition to requiring steam at the correct operating temperature, an SOE facility also requires an electrical energy input. For the SOE facility to produce clean hydrogen, this electrical energy input also needs to be considered clean.

The second method of integration involves the NPP supplying both thermal and electrical energy to the SOE facility. The heat extraction method remains the same across both methods of integration. However, an electrical tie-in is introduced in the switchyard to provide the needed electrical energy to the SOE facility. Westover et al. [10] proposed the high-voltage side of the NPP's generator step-up transformer as the tie-in site. The major components to construct this tie-in include a high-voltage circuit breaker, MOD switches, and a high-voltage transmission line. Westover et al. [10] also proposed the generator-isolated phase bus as an alternative tie-in point;

however, tapping the bus is expensive therefore the authors did not explore the option further. When considering both methods of integration, the next question becomes which is the more effective option, in terms of hydrogen production, efficiency and safe and reliable deployment.

In our analysis, we developed risk scenarios for a stand alone test-bed SOE system. In an effort to capture potential risk scenarios that could arise due to the integration of these systems, we considered the effects thermal cycling when an NPP was supplying high-temperature steam. An SOE facility coupled to an NPP would not be continuously in operation, therefore the SOE system can be in hot standby mode or be cycled through startup and shutdown. When certain issues, such as gaseous crossover, go unnoticed the thermal cycling of startup and shutdown procedures has the potential to exacerbate certain undesired consequences. However, we did not consider the second method of integration because the electrical input to the electrolyzer falls outside the system boundary and scope of our analysis.

Chapter 4: Identify Component Failure Modes and Risk Scenarios for a Solid Oxide Electrolyzer Facility

4.1 Introduction

In this chapter, we document our approach for identifying risk scenarios of an SOE facility via a comprehensive FMEA. An FMEA is a comprehensive, bottom-up approach used to identify risks associated with operational hazards of a design and determine which components contribute to the most high-risk scenarios. This method allows a team of engineers to discuss all of the relevant failure modes of a component and postulate the local, next higher level of abstraction and end effects of each failure mode [35]. Local effects are the effects the failure mode has on the function of that specific component. Meanwhile, the next level of abstraction and end effects describe the effect of a failure on downstream components and the overall system, respectively. The engineering team can organize the scenarios by component type, failure mode, and consequence type to generate insights into which areas of the system contribute to the most high-risk scenarios. We summarize all 650 risk scenarios identified and propose mitigation strategies. We synthesize the risk scenarios into a list of the 65 most critical scenarios. These results can be used by operators in early-stage deployments. The following chapter outlines the processes taken in planning, executing, and evaluating the results of the FMEA.

4.2 Approach for conducting the FMEA

Prior to conducting the FMEA, a system reference guide was developed to define key aspects of the methodology, the system boundary, and the scope of the analysis, determine the risk ranking, and establish relevant failure modes, mechanisms, and consequences. The purpose of this document was to ensure a consistent analysis of all components within the SOE system. The document kept the primary outcomes of the analysis at the forefront of the engineering team's minds. The two primary outcomes of the FMEA were building the foundation for a comprehensive QRA and providing critical insights for early development decisions. The FMEA was conducted with the knowledge that the resulting failure modes and risk scenarios would be leveraged in developing fault trees at a high level of abstraction. This allowed the engineering team to consider all relevant failure modes and the resulting consequences of each component within the electrolyzer system. The following section summarizes the reference document used in the FMEA.

4.2.1 Methodology

The primary goal of the FMEA was to identify failure scenarios, which serve as the initial step towards a complete QRA of an SOE facility. Secondly, providing a list of failure scenarios on a well-documented system allows for the potential scaling of results to commercial SOE facility designs. Additionally, the insights developed from the FMEA were leveraged to create fault trees at a high level of abstraction. To conduct the FMEA on an SOE facility design, we followed the IEC 60812 (2018) FMEA standard [34] and guidance from Modarres and Groth [35]. The approach to conduct this FMEA is as follows:

1. Plan the FMEA

    1.1 Assemble the necessary information and define the system, function, boundaries and operating conditions.

    1.2 Define the terms of reference, methodology and assemble a diverse team for the FMEA.

2. Perform the FMEA

    2.1 For each component, identify critical failure modes and their effects on the immediate function of the system.

    2.2 Assign a severity class by qualitatively evaluating the consequences of each failure mode.

    2.3 Assess the likelihood of occurrence of each failure mode on a defined scale.

    2.4 Identify current failure detection methods, safeguards and controls.

    2.5 Recommend actions to eliminate or control the risk.

3. Review additional literature surrounding the evaluation of Solid Oxide Electrolyzers and augment identified failure scenarios as necessary.

4. Document the analysis.

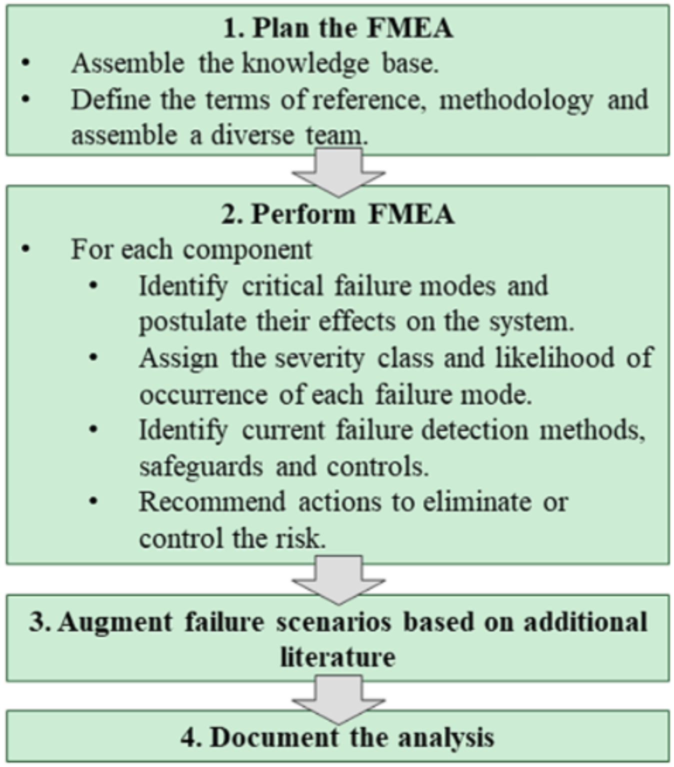

Figure 4.1: A summary of the FMEA process

4.2.2 Scope

This bottom-up FMEA reviews a normal operation scenario with active hydrogen recycling and the potential for mal-operation or malfunction of control instruments and safety systems for the system given in Figure 3.3. The black dashed line defines the system boundary. Components outside the system boundary were considered at a high level, either failed or operating, in our analysis. To better incorporate the coupling to a nuclear power plant, we documented the effect of startup and shutdown procedures on identified consequences in the FMEA. This section summarizes the necessary distinctions and assumptions made before conducting the FMEA.

The P&ID, in Figure 3.3, identifies the piping directly downstream of the steam generator to contain approximately 5% hydrogen by volume, which is needed to maintain the proper reducing conditions in the cathode. Due to the presence of hydrogen in this line, the piping and components directly downstream of the steam generator were considered part of the hydrogen functional group because of the potential for an accumulation of hydrogen. The original design from O'Brien et al. [16] used preheated air to continually sweep oxygen out of the anode side of the electrolyzer. In this analysis, all components associated with the sweeping of oxygen were considered part of the oxygen functional group. All hydrogen-containing components reside in a ventilated enclosure with a gas monitoring system for abnormal hydrogen and oxygen levels. In this analysis, the steam generator and DI water supply are considered. However, in large-scale deployments, steam would likely be produced on the nuclear island and instead require topping heat before reaching the electrolyzer stack.

O'Brien et al. [16] and Jorgensen [38] provided limited information regarding safety and control system (SCS), which discusses what transmitters trigger which systems. We considered the SCS to the level of depth of the information provided and introduced modifications based on prior knowledge of PEM electrolysis facility designs. The following description of the SCS was given in O'Brien et al. [16]. The gas monitoring system activates an alarm if hydrogen, elevated oxygen, or nitrogen levels are detected. The alarm signals are interlocked to a solenoid valve on the hydrogen gas supply line [16]. An alarm condition cuts off power to the electrolyzer stack and initiates the flow of the safe gas through the cathode to prevent oxidation. Laboratory occupants would be notified of the presence of a potentially hazardous buildup of gases by relay outputs, a display readout, visual and audible alarms, and an autodialer [16]. The SCS description provided a basis for identifying which sensors and transmitters are used in alarm conditions. However, to document which features of the SCS are barriers to each identified scenario, a trigger state is required. For each sensor and transmitter in Figure 3.3, the engineering team leveraged prior knowledge to determine an associated trigger state for each sensor, which are given in Table 4.1. Later, the engineering team confirmed the appropriateness of these assigned states with INL system operators.

Sensor	**Control Logic**
TT-01	No Associated Trigger
TT-02	Trigger Low/High
TT-03	Trigger Low/High
TT-04	Trigger Low/High
TT-05	Trigger Low/High
TT-06	Trigger Low/High
TT-07A/B/C	Trigger Low/High
TT-08A/B/C/D	Trigger Low/High
TT-09	Trigger Low/High
TT-10	Trigger Low/High
TT-11	Trigger Low/High
TT-12	Trigger Low/High
TT-13	Trigger Low/High
TT-14	Trigger Low/High
TT-15	Trigger Low/High
TT-16	Trigger Low/High
TT-17	No Associated Trigger
MF-01	Trigger Low Flow
MF-02	Trigger Low Flow
MF-03	Trigger Low Flow
MF-04	Trigger Low Flow
MF-05	Trigger Low Flow
PT-01	Trigger Low/High
PT-02	Trigger Low
PT-03	Trigger Low/High
OS-01	Trigger High
HS-01	Trigger High
WS-01	Trigger High
LI-01	Trigger Low/High
LI-02	Trigger Low/High

Table 4.1: Sensor control logic for the SOE facility

4.2.3 Failure Modes, Mechanisms and Consequences

The failure modes, which describe the ways in which components fail, were developed by West [40] and Groth et al. [41]. These failure modes were appended as needed based on prior electrolysis FMEA experience and relevant literature. A summary of failure modes used in this analysis are provided in Table 4.2. A predefined list of failure modes is used as a guide when analyzing to ensure all relevant failure modes were considered for every component within the system.

In addition to the failure modes listed in Table 4.2, the engineering team identified several other relevant failure modes, including full and partial plugging, full and partial freezing, leaks and ruptures of water, air, nitrogen or nitrogen and hydrogen mixtures. We make these distinctions because these failure modes have different local and next-highest level of abstraction effects on surrounding components. A full blockage results in a loss of water, meanwhile a partial blockage results in turbulent conditions that can dislodge surrounding components. The release of various process and utility mediums also poses varying hazards to facility personnel and the general population. These failure modes are detected in various ways, which were important to capture in the analysis as the safety and control system is necessary for developing the fault tree structures in Chapter 5.

Failure Mode	**Definition**
Abnormal output-high	Above normal output indicates potential failure(s)
Abnormal output-low	Below normal output indicates potential failure(s)
Bent/warped/damaged	Visible mechanical damage
Contamination	Component allows foreign material to contaminate product
Erratic output	Inconsistent output
External leak hydrogen	Hydrogen leak from within system to environment
External leak utility medium	Utility medium leak from the system to the environment
External rupture hydrogen	Complete loss of containment, hydrogen exhausts to the environment
External rupture utility medium	Complete loss of utility medium to the environment
Fail closed	Component stops working in the closed position
Fail open	Component stops working in the open position
Fail to close	Component does not close on demand
Fail to operate	Component does not function on demand
Fail to stop	Component does not stop on demand
Freezing	Component is frozen and becomes inoperable/requires maintenance
Plugging	Buildup of material restricting flow
Insufficient heat transfer	Target parameters for temperature are not met in a heat exchanger
Internal leak hydrogen	Hydrogen leak within system boundary (e.g. across a closed valve)
Internal leak utility medium	Utility medium leak within system boundary (e.g. across a closed valve)
Internal rupture hydrogen	Complete loss of containment, hydrogen stays within the system boundary
Internal rupture utility medium	Complete loss of containment, utility medium stays within the system boundary
Open circuit	Electrical circuit that is not complete
Overheating	Component is exposed to temperatures above design specifications
Restrict flow	Component is restricting flow when not intended to do so
Short circuit	Diversion of current
Spurious operation	Activation without specified demand (components normally idle)
Spurious stop	Stop without specified demand (components normally active)

Table 4.2: Primary failure modes considered in analysis adapted from West et al.[40]

To conduct the FMEA, a terms of reference document for the SOE system was created based guidance from Wismer et al. [36] to define the system, system boundary and establish relevant failure modes, causes and consequences. Each failure mode was paired with at least one failure mechanism. Wismer et al. [36] considered the following failure mechanisms and we supplemented as needed:

- Inadequate design, testing, manufacturing, installation, or maintenance
- Impurities in reactants and products
- Foreign debris/objects in water supply
- Abnormal output of the power supply
- Failure in an electrical or activation system
- External impacts
- External fires
- Overpressure
- Material degradation

For each failure mode and mechanism pair, the following consequences were considered:

- Hazardous release potentially leading to:
  - Fire
  - Explosion
  - Asphyxiation
- Dislodging/fracture of components due to an inertial release of process medium
- Membrane degradation that leads to a significant decrease in electrolyzer stack efficiency
- Loss of function

During the analysis, the loss of function of a component was considered, however, only scenarios resulting in potential hazardous hydrogen release, membrane degradation, hydrogen and oxygen mixing, and nitrogen release conditions are presented in the results. The release of a gas, either hydrogen or nitrogen, can pose a risk to the SOE facility and personnel. Due to hydrogen's low density, low minimum ignition energy, and wide flammability range of 4-75 vol% in the air [42], various consequences can manifest from a release. An undetected release in the presence of an ignition source can immediately ignite to create a jet fire or fireball. Alternatively, a delayed ignition would result in an explosion and overpressure event. The release of nitrogen into the facility will pose an asphyxiation hazard to facility personnel because nitrogen is colorless, odorless, and denser than air so it settles towards the ground, displacing the air [43]. Next, we considered membrane degradation due to the risk-critical hazards associated with operating a degraded stack. When a high-temperature electrolyzer stack membrane degrades, the voltage across a cell increases well beyond the thermo-neutral voltage, which elevates the internal temperature of the stack. Operating a degraded membrane can result in a mixture of hydrogen and oxygen in the electrolyzer stack. This flammable mixture can result in the combustion and subsequent burning of the electrolyzer cells during normal operation, as observed in [25]. Alternatively, should membrane degradation remain undetected during normal operation, more significant gaseous crossover can occur during or after the system has been cycled through startup and shutdown. Outside of normal operation, the electrolyzer stack is continuously flushed with a mixture of nitrogen, steam, and hydrogen. Therefore, this can result in an accumulation of hydrogen and oxygen mixture in the downstream hydrogen storage and compression subsystems.

4.2.4 Risk Ranking

The severity and likelihood of each failure scenario were evaluated using the risk matrix from Wismer et al. [36]. The matrix was used to address risks revolving around operator and general population safety. Each combination of likelihood of occurrence and severity result in a risk level ranging from negligible to high, for each scenario.

Severity					
	Catastrophic	Medium	High	High	High
	Serious	Low	Medium	High	High
	Moderate	Negligible	Low	Medium	High
	Minor	Negligible	Negligible	Low	Medium
	Insignificant	Negligible	Negligible	Negligible	Negligible
		Remote	Unlikely	Likely	Very Likely
		Occurrence			

Figure 4.2: Risk Matrix used by Wismer et al. [36]

The likelihood of occurrence of an event was defined as the occurrence per electrolyzer machine-year. Wismer et al. [36] defines an electrolyzer machine-year to be 4,000 operating hours based on an EU Joint Research Commission report [44] that estimated this value to be 3,000-5,000 operating hours per year. The likelihood of occurrence categories were defined as follows:

1. Remote – Failure expected to occur less than once in 1000 machine-years

2. Unlikely – Failure expected to occur less than once per 100 machine-years
3. Likely – Failure expected to occur more than once per 10 machine-years
4. Very Likely – Failure expected to occur more than once per machine-year

Severity categories consider the effect of an incident in a commercial scale SOE facility. This will aid in the future development of a complete QRA and scaling of results to full scale hydrogen facilities. The severity categories used in Wismer et al. [36] as follows:

1. Insignificant – no injury or illness
2. Minor – requiring first aid
3. Moderate – minor injury or illness requiring offsite medical treatment
4. Serious – serious bodily injury or serious work caused illness
5. Catastrophic – death or permanent disability

4.2.5 Analysis Approach

The engineering team was made up of a diverse group with experience in PEM electrolysis FMEAs, hydrogen safety, and PRA. Additionally, prior knowledge was leveraged in principles of reliability analysis and PRA to conduct a comprehensive analysis. The core group of three engineers conducted the analysis over multiple sessions. To complete the analysis, the core team of engineers gathered together for two-hour team meetings once a week over six months. The engineering team began the analysis by considering the first component (HV-01) within FG 1 and continuing on to consider each subsequent component individually by following the flow of the process medium through the system. For each component, the team consulted the list of failure modes given in Table 4.2 and identified all applicable modes that would lead to one of the consequences of interest. For each failure mode, we postulated the local, next highest level of abstraction and end effect on the overall system. Then, we assigned a likelihood of occurrence and severity based on the failure mode and resulting consequence. To further refine the developed risk scenarios, the core team consulted two additional engineers with backgrounds in hydrogen system safety to gain further insights into the exact function and purpose of particular components within the system. Lastly, we consulted system operators at INL to discuss unique features of the system design to capture any unique failure modes for those components.

4.3 Results: Failure Scenarios for a Solid Oxide Electrolyzer test facility by Functional Group

On the modal level we identified 650 failure scenarios, 495 of which were classified as high risk and 155 of which were medium risk. To display our results, we organized the scenarios by functional group, component type and failure type. The following categories of components were used to organize the results: condenser, electrolyzer, power supply, sensor, steam generator, valve and water trap. The following failure types were used to organize the scenarios: blockage, damage, electrical, leak, mechanical, rupture and thermal. A summary of the results across functional groups are shown in Figure 4.3. The complete FMEA is provided in the Appendix.

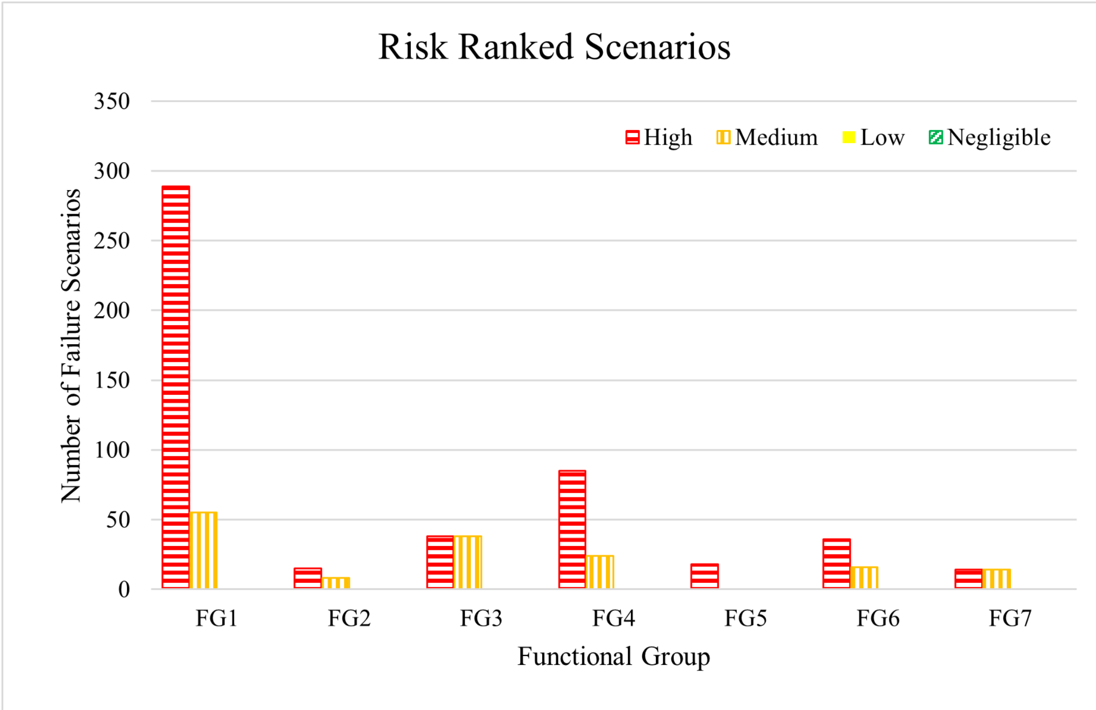

Figure 4.3: Identified failure scenarios organized by functional group

4.3.1 Functional Group 1: Water supply and Steam Generation Scenarios

Figure 4.4 presents all of the failure scenarios, organized by component type, for the DI water supply and steam generation functional group. There are 23 components considered in this functional group.

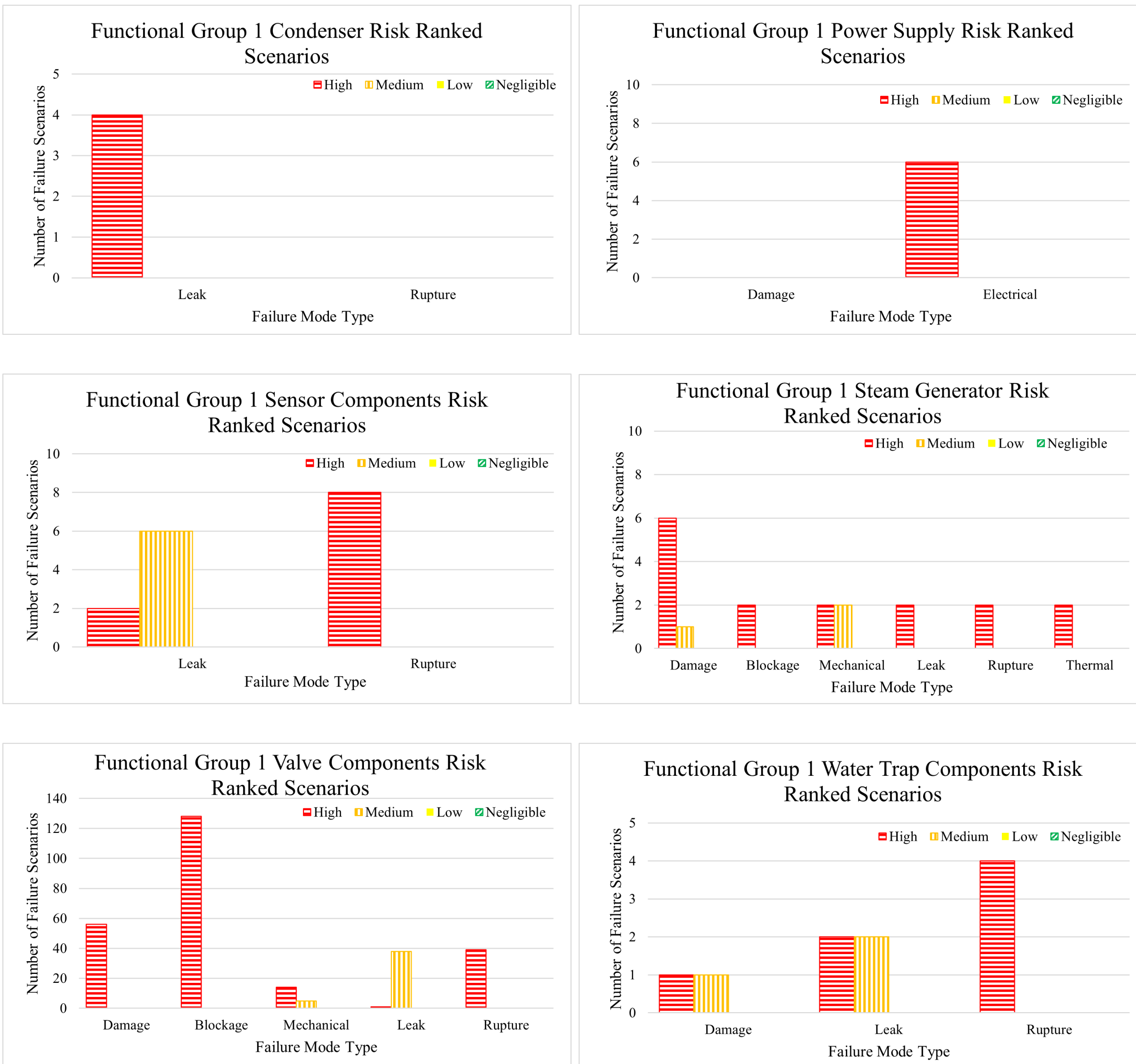

Figure 4.4: Summary of Functional Group 1 risk ranked scenarios by component type

4.3.2 Functional Group 2: High Temperature Electrolysis Scenarios

Figure 4.5 summarizes the risk scenarios of functional group 2. There are 5 components considered in this functional group. The majority of the scenarios are for the electrolyzer stack itself. However, as the technology continues to evolve and mature, the exact ways in which the electrolyzer stack fails may also change.

Figure 4.5: Summary of Functional Group 2 risk ranked scenarios by component type

4.3.3 Functional Group 3: Oxygen Processing and Production Scenarios

Figure 4.6 presents a summary of the risk scenarios for the oxygen processing and production functional group. There are 11 components considered in this functional group.

Figure 4.6: Summary of Functional Group 3 risk ranked scenarios by component type

4.3.4 Functional Group 4: Hydrogen Production and Recycle Scenarios

Figure 4.7 presents the risk scenarios for the hydrogen production and recycle functional group. There are 29 components considered in this functional group.

Figure 4.7: Summary of Functional Group 4 risk ranked scenarios by component type

4.3.5 Functional Group 5: Nitrogen Supply Scenarios

Figure 4.8 presents the risk scenarios for the nitrogen supply functional group. There are 8 components considered in this functional group.

Figure 4.8: Summary of Functional Group 5 risk ranked scenarios by component type

4.3.6 Functional Group 6: Chilled Water Supply Scenarios

Figure 4.9 summarizes the risk scenarios for the chilled water supply functional group. There are 4 components considered in this functional group.

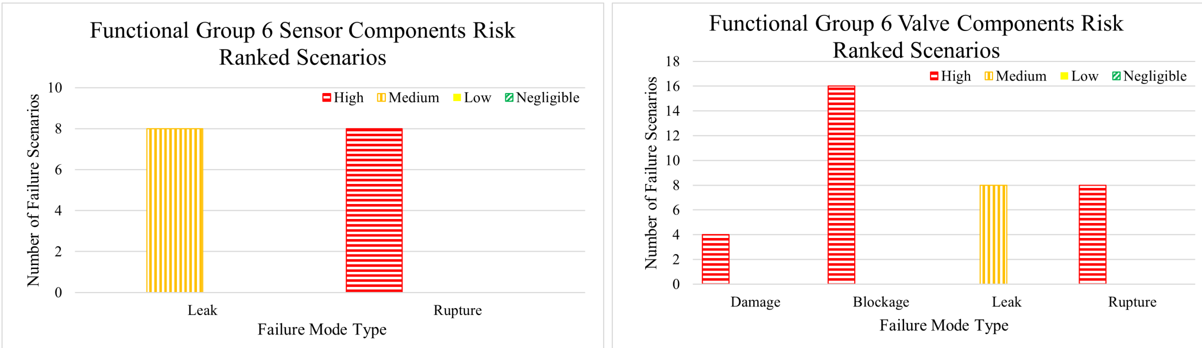

Figure 4.9: Summary of Functional Group 6 risk ranked scenarios by component type

4.3.7 Functional Group 7: Safe Gas Supply Scenarios

Figure 4.10 presents the risk scenarios for the safe gas supply functional group. There are 6 components considered in this functional group.

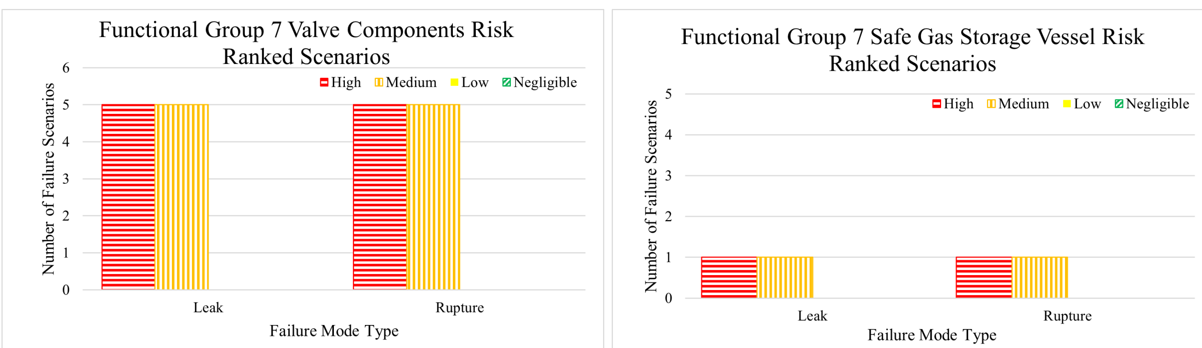

Figure 4.10: Summary of Functional Group 7 risk ranked scenarios by component type

4.4 Discussion and Conclusions

4.4.1 Insights from the Risk Scenarios

Functional Group 1, DI water supply and steam generation contributed to the most high-risk scenarios for this system, with 289 scenarios classified as high risk. Blockage failures of valve components resulted in a total of 128 high-risk scenarios. A blockage is either a full blockage or a partial blockage. The occurrence of a full blockage before the electrolyzer stack will result in steam starvation of the electrolyzer stack. Steam starvation has been shown to lead to membrane degradation [21, 45]. A partial blockage before the electrolyzer stack can cause turbulent conditions, which could dislodge surrounding components and starve the stack of steam. Before the condensers, a full blockage would result in improper cooling and drying of recycled hydrogen. Improper cooling results in recycled hydrogen at elevated temperatures, which causes a higher-than-intended temperature differential between the process medium and the electrolyzer stack. The temperature differential can stress the stack and result in accelerated membrane degradation during normal operation, ultimately decreasing the longevity of the stack. Degradation studies on SOE stacks have shown that increasing temperatures result in higher degradation rates [46]. Improper drying of recycled hydrogen can result in wet hydrogen entering the electrolyzer stack. A high-temperature SOE stack would experience degradation because these components are not designed for a liquid water environment. During normal operation, these conditions would result in membrane degradation, which can significantly reduce the efficiency. Additionally, during startup or shutdown, these conditions would result in a gaseous crossover with the potential for an accumulation of a combustible mixture in the hydrogen storage tank or a release of this mixture into the external environment.

Mitigation strategies for these failure modes will differ based on the blockage type. For full or partial freezing-type blockages, it is recommended that a robust heating and ventilation system be put in place to ensure suitable temperature control of the facility. Due to the acidic nature of DI water, corrosion of the inside of components can cause full or partial plugging and contamination-type failure modes to occur. Ensuring all components that interact with DI water are properly passivated is required to mitigate against these failure modes. Additionally, regular inspection of the steam generator is recommended to mitigate against undesired consequences because it is critical for the longevity of the electrolyzer stack that sufficient steam and hydrogen, within operating parameters, are present at the inlet.

In Functional Group 4, hydrogen production and recycling, there were 109 risk scenarios, 85 of which were classified as high-risk. Mechanical failures of valve components result in 20 high-risk scenarios, the largest number of scenarios of any component type in this functional group. A mechanical failure of a valve in the recycle portion of this functional group could starve the electrolyzer stack of the necessary hydrogen required at the inlet to maintain the proper reduction conditions and cause membrane degradation. To mitigate against these consequences, we recommend including an inline hydrogen detection sensor before the inlet of the stack to continuously monitor the volume of hydrogen. Outside of normal operation, the consequence of interest is the occurrence of gaseous crossover. During the analysis, we identified that the hydrogen and oxygen flammable gas mixture would accumulate in a downstream hydrogen storage tank (outside the system boundary shown in Figure 3.3) after the system is cycled through operating modes. During startup and shutdown procedures, the continued cycling of a degraded electrolyzer stack would exacerbate membrane degradation further. The occurrence of crossover becomes more likely outside of normal operation due to the potential of a varying pressure differential in the electrolyzer stack. However, crossover into the anode would result in the flammable mixture being vented directly to the hot zone and then swept to the outdoor environment. To detect the occurrence of significant crossover, we recommend an inline hydrogen detection sensor downstream of the anode side outlet to ensure that this flammable mixture does not pose undue harm to facility personnel.

We identified 76 risk scenarios in Functional Group 3, Oxygen processing and production, 38 of which were classified as high risk. The failure mode types of most concern for this functional group include leaks and ruptures of all components, mechanical failures of the air compressor or valves and thermal failures of the inline heaters. The leak and rupture failure modes can result in an accumulation of oxygen on the anode side due no sweep air flow. The buildup of pressure on the anode side can cause delamination of the oxygen electrode. Additionally, mechanical failures of the air compressor or valves would result in scenarios of excess sweep air flowing across the electrolyzer stack. These scenarios can result in an increased degradation rate [47]. Lastly, thermal failures of the inline heaters result in scenarios where the temperature differential between the sweep air and stack induces thermal stress to the stack. The safety and control system includes an inline mass flow controller (MF-04) that can detect abnormal flow upstream. However, to detect leaks and ruptures downstream of MF-04, we recommend a flow indicator prior to the anode inlet.

In Functional Group 6, the chilled water supply, we identified 52 risk scenarios, 36 of which were classified as high risk. Blockage failures in the valves resulted in the most high-risk scenarios. A blockage in this functional group would result in either insufficient drying or insufficient cooling of recycled hydrogen gas. As described previously, both wet hydrogen and above operating temperature hydrogen would impact the degradation rate of the membrane during normal operation. When the membrane is cycled through other operational modes, more significant gaseous crossover can occur which results in hydrogen and oxygen mixing. To mitigate these consequences, we recommend ensuring adequate control over the chiller and adequate installation and maintenance of the temperature transmitters.

Lastly, we identified 18 risk scenarios in Functional Group 5 and 28 risk scenarios in Functional Group 7. Both functional groups supply the system with primarily nitrogen outside normal operation. For Functional Group 5, the nitrogen supply, all 18 scenarios were high risk due to the potential for asphyxiation of facility personnel if a leak or rupture remains undetected. For Functional Group 7, the 14 high-risk scenarios were also due to the asphyxiation hazard posed by a nitrogen release. While the 14 medium risk scenarios were a result of the small amount of hydrogen, approximately 4%, that is present in the safe gas supply. Ensuring adequate gas detection systems will mitigate the risks posed by these consequences. Another potential barrier we recommend is individual nitrogen detection sensors that can be worn by facility personnel.

4.4.2 Synthesized List of Critical Risk Scenarios

We identified a total of 650 risk scenarios by conducting a comprehensive FMEA. In an effort to provide insights to early deployments, we synthesized the results into a list of critical risk scenarios, organized by consequence that are relevant to engineers as they continue to iterate on the design of SOE facilities. The list of the 65 critical risk scenarios is as follows:

1. **Membrane Degradation** which leads to a significant loss of efficiency during normal operation

   1.1 Obstruction to water flow can cause turbulent conditions and dislodging/fracture around components. This results in water starvation of SG-01 and steam starvation in ES-01 which leads to irreversible degradation of the membrane, mechanical damage of the membrane or cathode oxidation of ES-01.

   1.2 Obstruction to water flow can cause turbulent conditions and dislodging/fracture around components. Insufficient water level in the condensers can cause insufficient drying of H_2. Wet H_2 is fed back into ES-01 leading to accelerated membrane degradation.

1.3 Obstruction to water flow can cause turbulent conditions and dislodging/fracture around components. Insufficient water level in the condensers can cause insufficient cooling of H_2, which is fed back into ES-01 at above optimal temperature leading to accelerated membrane degradation.

1.4 Total obstruction of water flow causes water starvation of SG-01 and steam starvation in ES-01 which leads to irreversible degradation of the membrane, mechanical damage of the membrane or cathode oxidation of ES-01.

1.5 Total obstruction to water flow upstream of the condensers can cause insufficient drying of H_2. Wet H_2 is fed back into ES-01 leading to accelerated membrane degradation.

1.6 Total obstruction to water flow upstream of the condensers can cause insufficient cooling of H_2, which is fed back into ES-01 at above optimal temperature leading to accelerated membrane degradation.

1.7 Stagnation of water downstream of the condensers can cause insufficient drying of H_2. Wet H_2 is fed back into ES-01 leading to accelerated membrane degradation.

1.8 Stagnation of water downstream of the condensers can cause insufficient cooling of H_2, which is fed back into ES-01 at above optimal temperature leading to accelerated membrane degradation.

1.9 Release of water can cause water starvation of SG-01 and steam starvation of ES-01, which leads to irreversible degradation of the membrane, mechanical damage of the membrane or cathode oxidation of ES-01.

1.10 Release of water causes insufficient drying of H_2. Wet H_2 is fed back into ES-01 leading to accelerated membrane degradation.

1.11 Release of water causes insufficient cooling of H_2, which is fed back into ES-01 at above optimal temperature leading to accelerated membrane degradation.

1.12 Insufficient water flow into SG-01 causes steam starvation of ES-01, which leads to irreversible degradation of the membrane, mechanical damage of the membrane or cathode oxidation of ES-01.

1.13 Insufficient seal with downstream piping causes steam starvation over time, which leads to irreversible degradation of the membrane, mechanical damage of the membrane or cathode oxidation of ES-01.

1.14 Insufficient seal with upstream piping causes water starvation of SG-01 and steam starvation of ES-01, which leads to irreversible degradation of the membrane, mechanical damage of the membrane or cathode oxidation of ES-01.

1.15 Loss of steam production in SG-01 causes steam starvation which leads to irreversible degradation of the membrane, mechanical damage of the membrane or cathode oxidation of ES-01.

1.16 SG-01 produces insufficient quantities of steam, which can cause steam starvation which leads to irreversible degradation of the membrane, mechanical damage of the membrane or cathode oxidation of ES-01.

1.17 H_2 is not present at the inlet of ES-01, which can cause improper reducing conditions and can lead to accelerated membrane degradation.

1.18 In-line components, in FG 1, prior to ES-01 heat steam and H_2 mixture to above optimal temperatures, which can cause accelerated membrane degradation.

1.19 Insufficient cooling in AC-01A/B/C can cause improper cooling H_2 which results in above optimal temperature H_2 at the inlet of ES-01. This can cause accelerated membrane degradation.

1.20 Insufficient gas removal from ES-01 can cause accelerated membrane degradation and the loss of the H_2 recycle system.

1.21 A blockage of the cathode outlet results in accumulation of H_2 in ES-01. This can cause an increase in pressure which leads to irreversible degradation of the membrane, mechanical damage of the membrane or cathode oxidation of ES-01.

1.22 Internal leak of hydrogen can lead to oxidation of the cathode, Nickel depletion or damage to the membrane of ES-01.

1.23 High output from the power supply for ES-01 can cause thermal damage to the membrane or accelerated degradation of ES-01.

1.24 A lack of sweep air results in accumulation of oxygen in the anode of ES-01. This leads to a buildup of pressure which can cause irreversible membrane degradation, including delamination.

1.25 Excess air has the potential to expose the anode electrode to boron, sulfur or silica which can cause irreversible membrane degradation of ES-01 through poisoning.

1.26 In-line components, in FG 3, prior to ES-01 heat sweep air to above optimal temperatures, which can cause accelerated membrane degradation.

1.27 Accumulation of H_2 in PH-5 results in CO-1 unable to supply V-01 with the correct amount of H_2. Over time, V-01 will drain and cause an insufficient amount of H_2 at the inlet of ES-01. Which can cause improper reducing conditions and can lead to accelerated membrane degradation.

1.28 Accumulation of H_2 in PH-6 results in the loss of H_2 recycle system. Overtime, this can cause less then 5% H_2 at the inlet of ES-01, which can cause improper reducing conditions and can lead to accelerated membrane degradation.

1.29 High output from CO-01 can create a vacuum upstream which can cause H_2 to flow through the drying and cooling components at a faster then intended rate. This can cause insufficient cooling of H_2, which is fed back into ES-01 at above optimal temperature leading to accelerated membrane degradation.

2. **Hydrogen Release**

2.1 External release of H_2.

2.2 Release of water from a component causes an insufficient water seal which provides a path for H_2 to escape into the atmosphere.

2.3 Insufficient seal with downstream piping provides a path for H_2 to escape into the atmosphere.

2.4 Accumulation of H_2 in V-01 beyond the holding capacity of the vessel which provides a potential path for H_2 to escape into the atmosphere.

2.5 Accumulation of H_2 in PH-6, which can cause H_2 to back feed into upstream components which provides a potential path for H_2 to escape into the atmosphere.

3. **Oxygen and Hydrogen Mixing**

3.1 Insufficient gas removal from ES-01 can cause an increase in pressure in ES-01 which can lead to a rupture of the membrane and the occurrence of a flammable mixture of oxygen and hydrogen during normal operation.

3.2 Accumulation of H_2 in PH-5 can result in the back feeding of hydrogen into ES-01. This can cause an increase in pressure in the cathode which could lead to a rupture of the membrane and the occurrence of a flammable mixture of oxygen and hydrogen during normal operation.

3.3 Obstruction to water flow can cause turbulent conditions and dislodging/fracture around components. This results in water starvation of SG-01 and steam starvation in ES-01 which leads to irreversible degradation of the membrane and the occurrence of significant crossover outside of normal operation.

3.4 Obstruction to water flow can cause turbulent conditions and dislodging/fracture around components. Insufficient water level in the condensers can cause insufficient drying of H_2. Wet H_2 is fed back into ES-01 leading to accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

3.5 Obstruction to water flow can cause turbulent conditions and dislodging/fracture around components. Insufficient water level in the condensers can cause insufficient cooling of H_2, which is fed back into ES-01 at above optimal temperature leading to accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

3.6 Total obstruction of water flow causes water starvation of SG-01 and steam starvation in ES-01 which leads to irreversible degradation of the membrane and the occurrence of significant crossover outside of normal operation.

3.7 Total obstruction to water flow upstream of the condensers can cause insufficient drying of H_2. Wet H_2 is fed back into ES-01 leading to accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

3.8 Total obstruction to water flow upstream of the condensers can cause insufficient cooling of H_2, which is fed back into ES-01 at above optimal temperature leading to accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

3.9 Stagnation of water downstream of the condensers can cause insufficient drying of H_2. Wet H_2 is fed back into ES-01 leading to accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

3.10 Stagnation of water downstream of the condensers can cause insufficient cooling of H_2, which is fed back into ES-01 at above optimal temperature leading to accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

3.11 Release of water can cause water starvation of SG-01 and steam starvation of ES-01, which leads to irreversible degradation of the membrane and the occurrence of significant crossover outside of normal operation.

3.12 Release of water causes insufficient drying of H_2. Wet H_2 is fed back into ES-01 leading to accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

3.13 Release of water causes insufficient cooling of H_2, which is fed back into ES-01 at above optimal temperature leading to accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

3.14 Insufficient water flow into SG-01 causes steam starvation of ES-01, which leads to irreversible degradation of the membrane and the occurrence of significant crossover outside of normal operation.

3.15 Insufficient seal with downstream piping causes steam starvation over time, which leads to irreversible degradation of the membrane and the occurrence of significant crossover outside of normal operation.

3.16 Insufficient seal with upstream piping causes water starvation of SG-01 and steam starvation of ES-01, which leads to irreversible degradation of the membrane and the occurrence of significant crossover outside of normal operation.

3.17 Loss of steam production in SG-01 causes steam starvation which leads to irreversible degradation of the membrane and the occurrence of significant crossover outside of normal operation.

3.18 SG-01 produces insufficient quantities of steam, which can cause steam starvation which leads to irreversible degradation of the membrane and the occurrence of significant crossover outside of normal operation.

3.19 H_2 is not present at the inlet of ES-01, which can cause improper reducing conditions and the occurrence of significant crossover outside of normal operation.

3.20 In-line components,in FG 1, prior to ES-01 heat steam and H_2 mixture to above optimal temperatures, which can cause accelerated membrane degradation.

3.21 Insufficient cooling in AC-01A/B/C can cause improper cooling H_2 which results in above optimal temperature H_2 at the inlet of ES-01. This can cause accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

3.22 A blockage of the cathode outlet results in accumulation of H_2 in ES-01. This can cause an increase in pressure which leads to irreversible degradation of the membrane and the occurrence of significant crossover outside of normal operation.

3.23 Internal leak of hydrogen can lead to oxidation of the cathode, Nickel depletion or damage to the membrane of ES-01 and the occurrence of significant crossover outside of normal operation.

3.24 High output from the power supply for ES-01 can cause thermal damage to the membrane or accelerated degradation of ES-01 and the occurrence of significant crossover outside of normal operation.

3.25 A lack of sweep air results in accumulation of oxygen in the anode of ES-01. This leads to a buildup of pressure which can cause irreversible membrane degradation of ES-01 and the occurrence of significant crossover outside of normal operation.

3.26 Excess air has the potential to expose the anode electrode to boron, sulfur or silica which can cause irreversible membrane degradation of ES-01 and the occurrence of significant crossover outside of normal operation and the occurrence of significant crossover outside of normal operation.

3.27 In-line components,in FG 3, prior to ES-01 heat sweep air to above optimal temperatures, which can cause accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

3.28 Accumulation of H_2 in PH-5 results in CO-1 unable to supply V-01 with the correct amount of H_2. Over time, V-01 will drain and cause an insufficient amount of H_2 at the inlet of ES-01. Which can cause improper reducing conditions and can lead to accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

3.29 Accumulation of H_2 in PH-6 results in the loss of H_2 recycle system. Overtime, this can cause less then 5% H_2 at the inlet of ES-01, which can cause improper reducing conditions and can lead to accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

3.30 High output from CO-01 can create a vacuum upstream which can cause H_2 to flow through the drying and cooling components at a faster then intended rate. This can cause insufficient cooling of H_2, which is fed back into ES-01 at above optimal temperature leading to accelerated membrane degradation and the occurrence of significant crossover outside of normal operation.

4. **Nitrogen Release**

4.1 External release of Nitrogen

4.4.3 Conclusions

This chapter provides a comprehensive set of relevant failure modes for over 80 components of an SOE facility spanning seven functional groups. We documented our approach and presented all 650 identified risk scenarios, organized by functional group, component type, failure type and risk ranking. A thorough FMEA is a necessary step to establish the foundational knowledge of SOE system failure. The results highlight that component failures within the balance of plant could manifest as a hydrogen release, degraded membrane, hydrogen and oxygen mixing or nitrogen release. When undetected, a degraded membrane can contribute to the occurrence of gaseous crossover, resulting in the mixture and accumulation of hydrogen and oxygen. The occurrence of either consequence depends on which symptoms operators are able to identify and diagnose first. To support early deployments, we synthesized the FMEA results into a list of 65 critical scenarios to provide a readily available record that can be adapted into a checklist of key failures.

The FMEA provides a comprehensive set of risk scenarios however, the method is largely qualitative and relies heavily on expert judgment. Alone, this set of risk scenarios cannot provide insight into critical components or subsystems that could improve the reliable up-time of SOE systems. To lay the foundations for providing future design recommendations with QRA, we must go beyond the FMEA to create system failure understanding and logic. This motivates the need for Fault Tree Analysis, which can identify combinations of critical component failure modes that lead to specific undesired system failures. These critical combinations of failures can provide early deployments with targeted insights into ensuring the safe and reliable operation of SOE systems.

Chapter 5: Identify Critical Combinations of Failure Modes for a Solid Oxide Electrolyzer Facility

5.1 Introduction

This chapter discusses our approach for identifying the most significant areas of failure within the SOE system using fault tree analysis. The fault tree method is an approach to postulate an undesirable event, also called a top event, and deduce all of the possible ways that event can occur systematically [35]. Boolean algebra is then employed to determine the failure logic by generating cut sets through the use of the successive substitution method. The primary goals of the fault tree analysis were to establish the failure understanding and logic for an SOE system at a high level of abstraction, provide a visual display of combinations of critical component failures, and identify the most significant safety and control systems. We present the fault tree structures for six different top events that can occur in either normal operation, startup, shutdown or hot standby operation. We qualitatively evaluate the fault tree structures to determine the minimal cut sets, which identified combinations of component failures, including the critical safety and control systems required to ensure safe and reliable operation of SOE facilities. We go beyond developing risk scenarios to develop fault tree structures that display relevant component failure modes as a basis for subsequent quantification in QRA.

5.2 Methodology and Approach

We created these fault tree structures in accordance to guidelines from Modarres and Groth [35] and the NUREG fault tree handbook [37]. The following process is used to conduct a fault tree analysis:

1. Define the system being analyzed
2. Define the top event
3. Construct the fault tree
4. Perform the qualitative evaluation
5. Perform the quantitative evaluation

In this work, we complete steps one through four of the fault tree analysis process. Fault trees use three types of symbols in their construction: events, gates, and transfers. The events used in our fault tree structures include basic events, undeveloped events, and intermediate events. Basic events are represented by a circle and defined as an event that requires no further development [35]. An undeveloped event is represented by a diamond and defined as an event that is not developed further due to insufficient consequence or a lack of necessary information [35]. An intermediate event is represented by a rectangle and defined as an event that occurs due to antecedent causes acting through the logic gates [35]. At a high level of abstraction, the basic events include specific components and their undesired state. Alternatively, the undeveloped events are for major groupings of components, such as pipes and fittings or a group of valves. The fault tree structures use logic gates to describe the ways in which events need to occur. We primarily use two types of gates: (1) AND gates and (2) OR gates. When a specific output requires all input events to occur together, this is represented using an AND gate. Conversely, when an output requires at least one of the input events to occur, this is represented by an OR gate. Lastly, transfers are used when the fault trees become too large to be displayed on a single page. Due to the high level of abstraction, each fault tree is presented on a single page in the following section. The symbols used in our fault tree construction are summarized in Figure 5.1.

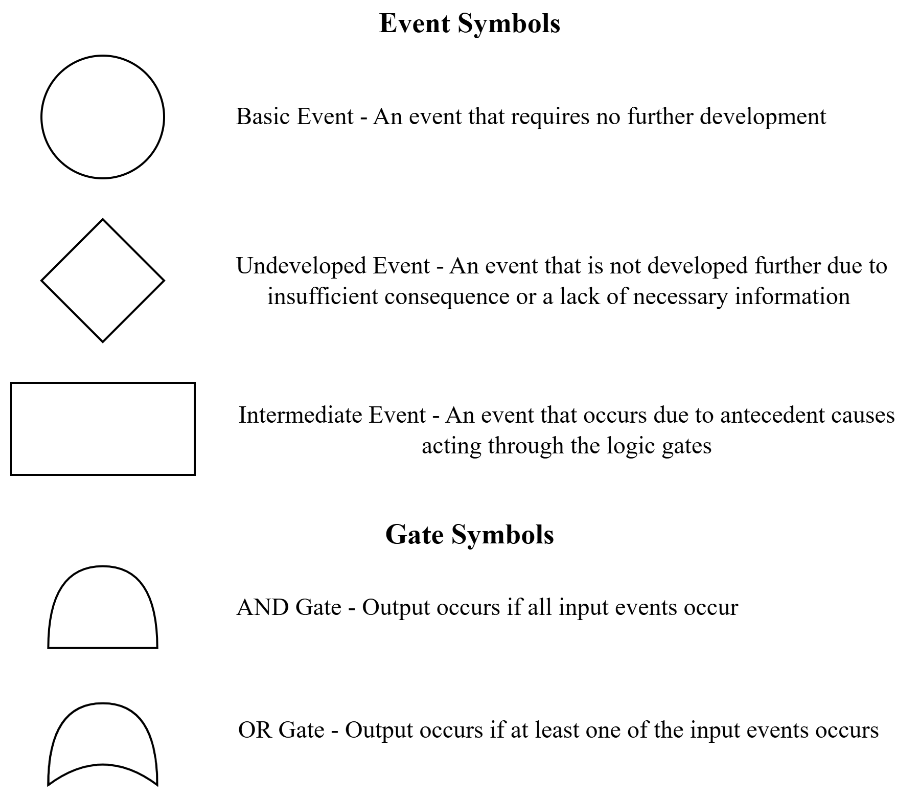

Figure 5.1: Primary event and gate symbols used in the construction of these fault trees adapted from Modarres and Groth [35]

Chapter 3 defined the system we analyzed. The top events of interest are a release of hydrogen, membrane degradation resulting in a significant decrease in electrolyzer stack efficiency, hydrogen and oxygen mixing outside of normal operation, and a nitrogen release outside of normal operation. To construct the fault trees, the 650 risk scenarios identified through the FMEA were grouped by consequence type. Within each consequence type, the scenarios were further grouped by end effect on the system. These end effects became the major branches within each fault tree. These sub-groupings of risk scenarios helped identify which component and failure mode pairs resulted in a specific source of failure. The sub-groupings also highlighted which features of the safety and control systems needed to fail for the failure mode to remain undetected. The process was repeated for all of the top events of interest. After creating the fault tree structures, the qualitative evaluation used Boolean logic to develop the minimal cut sets. The following section presents the minimal cut sets for each top event. These fault trees and minimal cut sets provide a foundation for how these top events can manifest within the system. The cut sets are a means to understand the failure logic and provide the combinations of critical component failures. The qualitative evaluation contributes to the understanding of how failures in specific areas of the system lead to specific system failures.

5.3 Results: Fault Tree Structures for a Solid Oxide Electrolyzer Test facility

5.3.1 Leak of 95% Steam, 5% Hydrogen Mixture during Normal Operation

The presence of a small amount of hydrogen at the inlet of the electrolyzer stack requires the distinction to be made between a leak of a 95% steam, 5% hydrogen mixture, a minor release and a major release of hydrogen. We chose to classify a release of this steam and hydrogen mixture separately from a minor release of hydrogen due to the small amount of hydrogen present in these pipe segments and the amount of time required for a leak of this mixture to trigger the safety and control system. The fault tree is presented in Figure 5.2 and the minimal cut sets are given in Table 5.1. There are a total of 12 minimal cut sets for a release of a steam and hydrogen mixture, 10 of which are order 2 cut sets. This means that 10 combinations of only two component failures will lead to the occurrence of this undesired system failure.

Rank	**Cut Set**	**Order**
1	GH-01 Leak · HS-01 Fail to Operate	2
2	LI-01 Leak · HS-01 Fail to Operate	2
3	TT-01 Leak · HS-01 Fail to Operate	2
4	TT-02 Leak · HS-01 Fail to Operate	2
5	TT-03 Leak · HS-01 Fail to Operate	2
6	TT-04A Leak · HS-01 Fail to Operate	2
7	WT-01 Leak · HS-01 Fail to Operate	2
8	Poor Seal between WT-01 and PH-1 · HS-01 Fail to Operate	2
9	Poor Seal between SG-01 and PH-1 · HS-01 Fail to Operate	2
10	Pipes and Fittings Leak · HS-01 Fail to Operate	2
11	HV-05 Leak · WS-01 Fail to Operate · HS-01 Fail to Operate	3
12	HV-06 Leak · WS-01 Fail to Operate · HS-01 Fail to Operate	3

Table 5.1: Minimal cut sets of the 95% Steam 5% Hydrogen Release fault tree

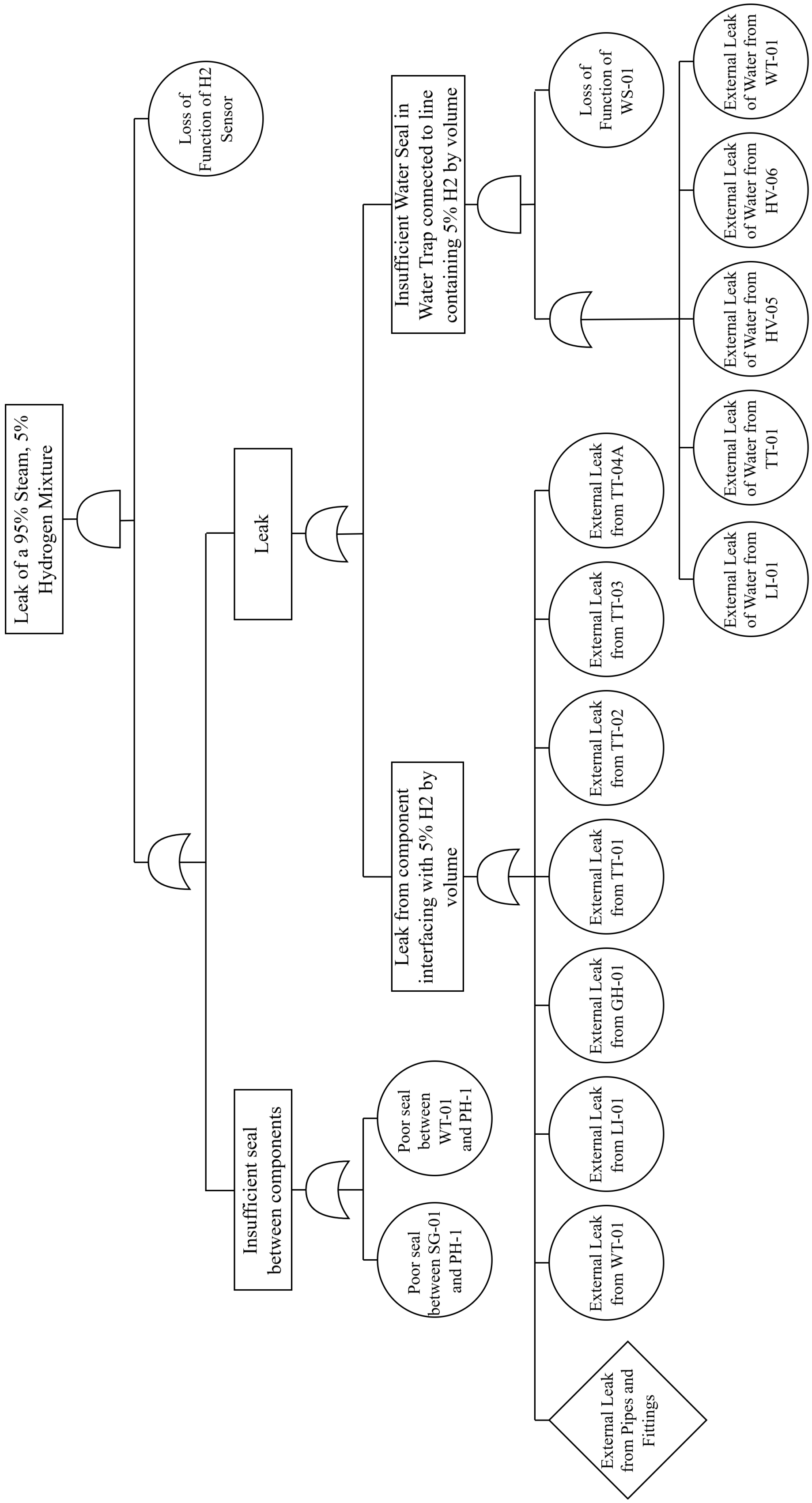

Figure 5.2: Overview of the 95% steam 5% hydrogen release fault tree for normal operating conditions

5.3.2 Minor Release of Hydrogen during Normal Operation

Using guidance from the HyRAM+ technical guide [48] and the National Fire Protection Association Hydrogen Technologies Code (NFPA 2) [49], we define a leak of 0.01% to 10% of the pipe flow area as a small or minor leak. Current definitions for minor and major releases are being developed as the technology continues to progress. We understand that as the technology becomes more mature, the definitions may change. However, we are utilizing the best available definitions in an effort to distinguish between minor and major releases of hydrogen that can occur in our system. The fault tree is presented in Figure 5.3 and the minimal cut sets are given in Table 5.2. A total of 22 minimal cut sets were identified, 14 of which are order 2 cut sets. Therefore, 14 combinations of only two component failures will lead to the occurrence of a minor release of hydrogen. There are also 10 order 3 cut sets, which describe paths when three component failures lead to this undesired system failure.

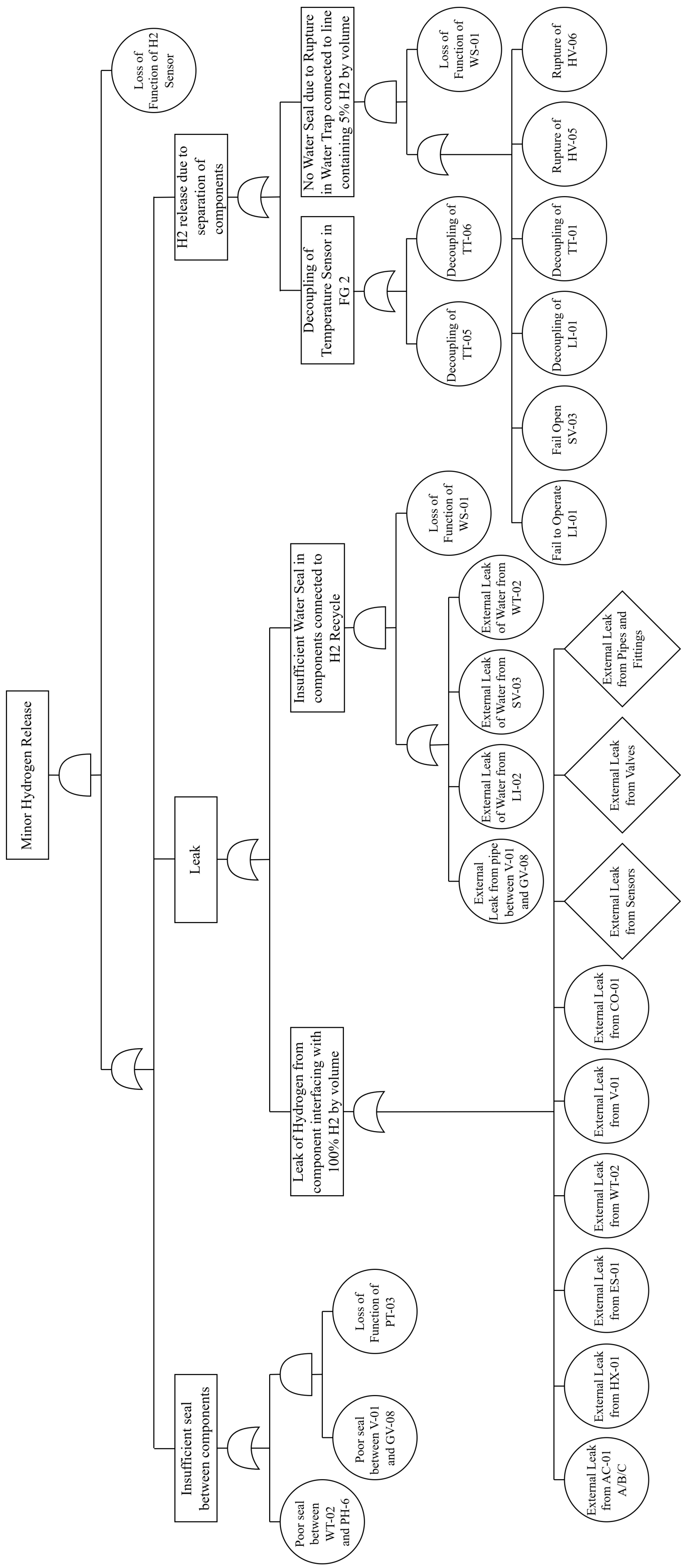

Figure 5.3: Overview of the minor hydrogen release fault tree for normal operating conditions

Rank	Cut Set	Order
1	AC-01 A/B/C Leak · HS-01 Fail to Operate	2
2	CO-01 Leak · HS-01 Fail to Operate	2
3	ES-01 Leak · HS-01 Fail to Operate	2
4	HX-01 Leak · HS-01 Fail to Operate	2
5	V-01 Leak · HS-01 Fail to Operate	2
6	WT-02 Leak · HS-01 Fail to Operate	2
7	Valves Leak · HS-01 Fail to Operate	2
8	Sensors Leak · HS-01 Fail to Operate	2
9	Pipes and Fittings Leak · HS-01 Fail to Operate	2
10	TT-05 Decoupling · HS-01 Fail to Operate	2
11	TT-06 Decoupling · HS-01 Fail to Operate	2
12	Poor Seal between WT-02 and PH-6 · HS-01 Fail to Operate	2
13	LI-02 Leak · WS-01 Fail to Operate · HS-01 Fail to Operate	3
14	SV-03 Leak · WS-01 Fail to Operate · HS-01 Fail to Operate	3
15	Leak between V-01 and GV-08 · WS-01 Fail to Operate · HS-01 Fail to Operate	3
16	Poor Seal between V-01 and GV-08 · PT-03 Fail to Operate · HS-01 Fail to Operate	3
17	LI-01 Decoupling · WS-01 Fail to Operate · HS-01 Fail to Operate	3
18	TT-01 Decoupling · WS-01 Fail to Operate · HS-01 Fail to Operate	3
19	LI-01 Fail to Operate · WS-01 Fail to Operate · HS-01 Fail to Operate	3
20	SV-03 Fail Open · WS-01 Fail to Operate · HS-01 Fail to Operate	3
21	HV-05 Rupture · WS-01 Fail to Operate · HS-01 Fail to Operate	3
22	HV-06 Rupture · WS-01 Fail to Operate · HS-01 Fail to Operate	3

Table 5.2: Minimal cut sets of the Minor Hydrogen Release fault tree

5.3.3 Major Release of Hydrogen during Normal Operation

We define a major hydrogen release as an occurrence when 100% of the pipe cross-sectional area is open and releasing hydrogen into the environment, based on guidance from the HyRAM+ technical guide [48] and the National Fire Protection Association Hydrogen Technologies Code (NFPA 2) [49]. The constructed fault tree is presented in Figure 5.4 and the minimal cut sets are given in Table 5.3. A total of 17 minimal cut sets were identified via the qualitative evaluation of this fault tree. There are 9 order 2 cut sets, meaning that there are 9 combinations of only two component failures that will lead to the occurrence of a minor release of hydrogen. There are also nine order 3 cut sets and one order 4 cut set.

Rank	Cut Set	Order
1	CO-1 Rupture · HS-01 Fail to Operate	2
2	Pipes and Fittings Rupture · HS-01 Fail to Operate	2
3	Sensor Decoupling · HS-01 Fail to Operate	2
4	AC-01 A/B/C Rupture · HS-01 Fail to Operate	2
5	ES-01 Rupture · HS-01 Fail to Operate	2
6	HX-01 Rupture · HS-01 Fail to Operate	2
7	Valves Rupture · HS-01 Fail to Operate	2
8	V-01 Rupture · HS-01 Fail to Operate	2
9	Water Trap Rupture · HS-01 Fail to Operate	2
10	CV-06 Fail Closed · PV-05 A/B/C Fail to Operate · HS-01 Fail to Operate	3
11	WS-01 Fail to Operate · LI-01 Fail to Operate · HS-01 Fail to Operate	3
12	WS-01 Fail to Operate · SV-03 Fail Open · HS-01 Fail to Operate	3
13	WS-01 Fail to Operate · LI-02 Rupture · HS-01 Fail to Operate	3
14	WS-01 Fail to Operate · SV-03 Rupture · HS-01 Fail to Operate	3
15	WS-01 Fail to Operate · WT-01 Rupture · HS-01 Fail to Operate	3
16	WS-01 Fail to Operate · WT-02 Rupture · HS-01 Fail to Operate	3
17	BPR-05 Fail to Operate · PRV-06 Fail to Operate · PT-03 Fail to Operate · HS-01 Fail to Operate	4

Table 5.3: Minimal cut sets of the Major Hydrogen Release fault tree

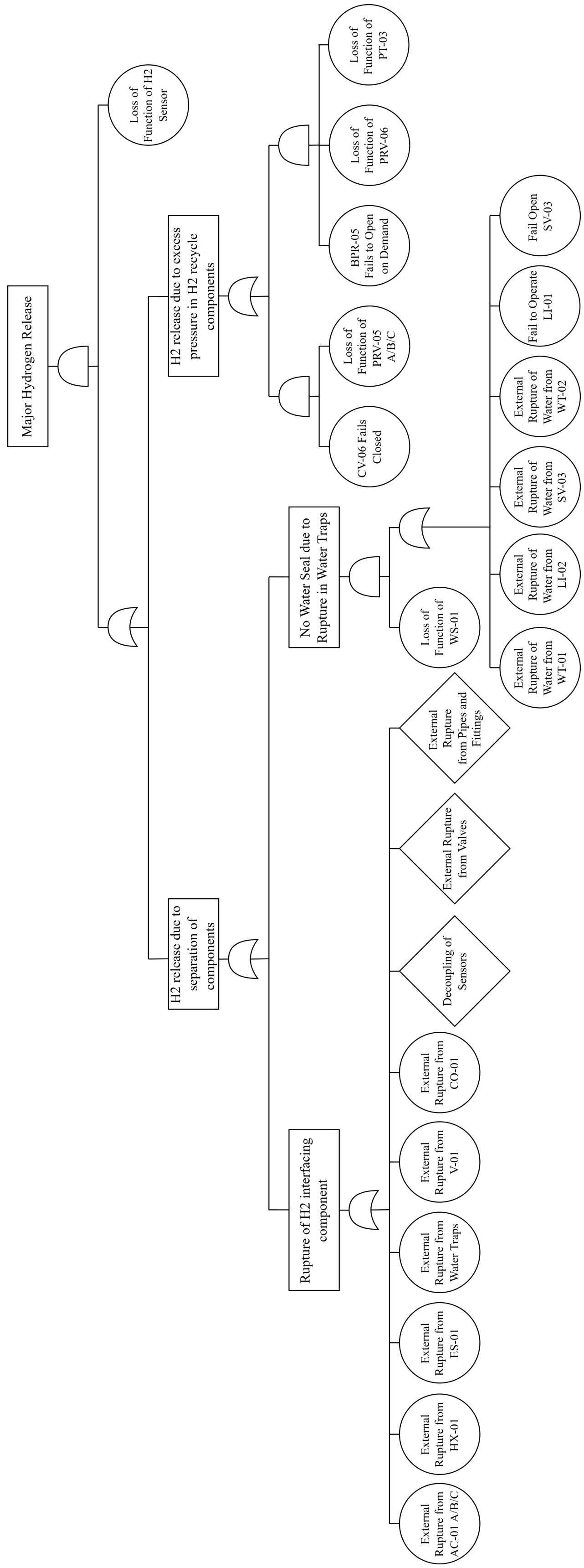

Figure 5.4: Overview of the major hydrogen release fault tree for normal operating conditions

5.3.4 Membrane Degradation during Normal Operation

Membrane degradation is defined as the irreversible gradual decline of the electrolyzer stack's membrane due to various environmental and operational factors that reduce the stack's performance, durability, and efficiency over time. This definition was developed using guidance from Modarres et al. [50]. Membrane degradation is an important top event of interest because a severely degraded membrane will result in costly system downtime. The fault tree is presented in Figure 5.5 and the minimal cut sets are given in Table 5.4. A total of 16 minimal cut sets that lead to the occurrence of membrane degradation were identified. There are 13 order 2 cut sets, meaning that there are 13 combinations of only two component failures that will lead to the occurrence of a minor release of hydrogen. There are also 3 order 3 cut sets, which describe paths when three component failures lead to this top event.

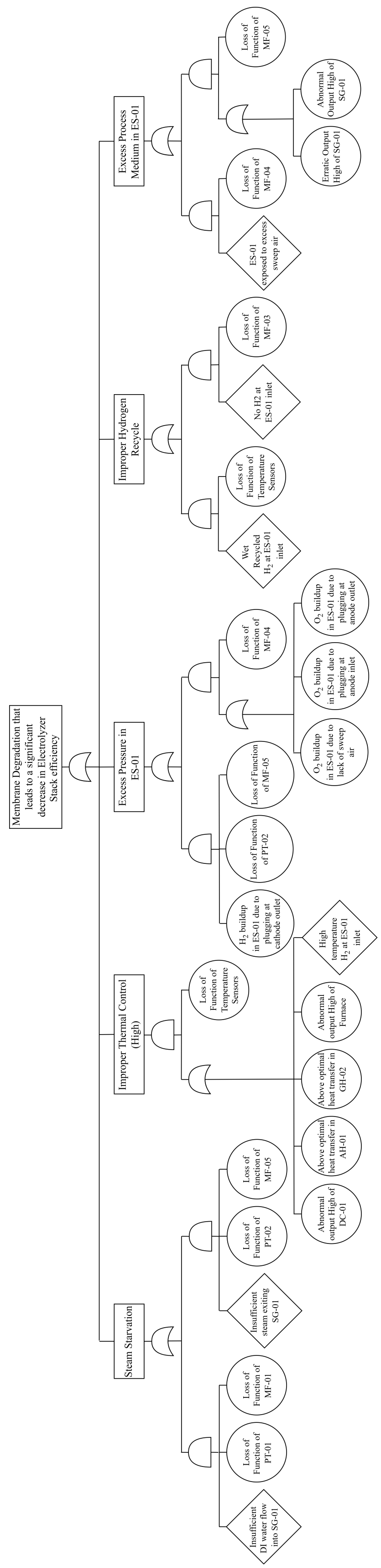

Figure 5.5: Overview of the membrane degradation fault tree for normal operating conditions

Rank	Cut Set	Order
1	ES-01 Excess Sweep Air · MF-04 Fail to Operate	2
2	Oxygen buildup due plugging at outlet of ES-01 · MF-04 Fail to Operate	2
3	Oxygen buildup due plugging at inlet of ES-01 · MF-04 Fail to Operate	2
4	Oxygen buildup in ES-01 due to lack of sweep air · MF-04 Fail to Operate	2
5	Wet H_2 in ES-01 · MF-03 Fail to Operate	2
6	High temperature H_2 at ES-01 inlet · Temperature Sensor Fail to Operate	2
7	No H_2 at ES-01 inlet · MF-03 Fail to Operate	2
8	AH-01 Above Optimal Heat Transfer · Temperature Sensor Fail to Operate	2
9	GH-02 Above Optimal Heat Transfer · Temperature Sensor Fail to Operate	2
10	DC-01 Abnormal Output High · Temperature Sensor Fail to Operate	2
11	Furnace Abnormal Output High · Temperature Sensor Fail to Operate	2
12	SG-01 Abnormal Output High · MF-05 Fail to Operate	2
13	SG-01 Erratic Output High · MF-05 Fail to Operate	2
14	H_2 buildup due to plugging at outlet of ES-01 · PT-02 Fail to Operate · MF-05 Fail to Operate	3
15	SG-01 produces insufficient steam · PT-02 Fail to Operate · MF-05 Fail to Operate	3
16	Insufficient DI water flow into SG-01 · PT-01 Fail to Operate · MF-01 Fail to Operate	3

Table 5.4: Minimal cut sets of the Membrane Degradation fault tree

5.3.5 Oxygen and Hydrogen Mixing Outside of Normal Operation

Leveraging insights gained from experts at INL, the consequence of gaseous crossover within the membrane that can lead to the creation and accumulation of a flammable mixture of oxygen and hydrogen is more likely to occur during startup or shutdown rather then in normal operation. The high temperature environment within the stack creates a highly reactive environment. The experts at INL discussed that the highly reactive nature of all substances within the furnace would essentially minimize any occurrence of a flammable mixture. At the operating temperature of 800 °C, any gaseous crossover that occurs would simply recombine into steam. When this occurs on the cathode side, there is more steam present in the mixture than anticipated, which has the potential to degrade the membrane. Meanwhile in the anode, this mixture would be vented to the furnace enclosure before being vented to the exterior of the laboratory. However, during the process of startup or shutdown when the electrolyzer stack is not at operating temperature, gaseous crossover becomes a consequence of concern due to the potential of accumulation of the flammable mixture downstream in a storage tank and results in fires or explosions when an ignition source is present. If the top event manifests outside of normal operation and remains undetected, a flammable mixture of hydrogen and oxygen can accumulate in V-01 during normal operation. The fault tree is presented in Figure 5.6 and all of the 13 minimal cut sets are given in Table 5.5. There are 10 order 3 cut sets, meaning that there are 10 combinations of three components failures that will lead to the occurrence of a minor release of hydrogen. There are also three order 4 cut sets, which describe paths where four component failures lead to the top event.

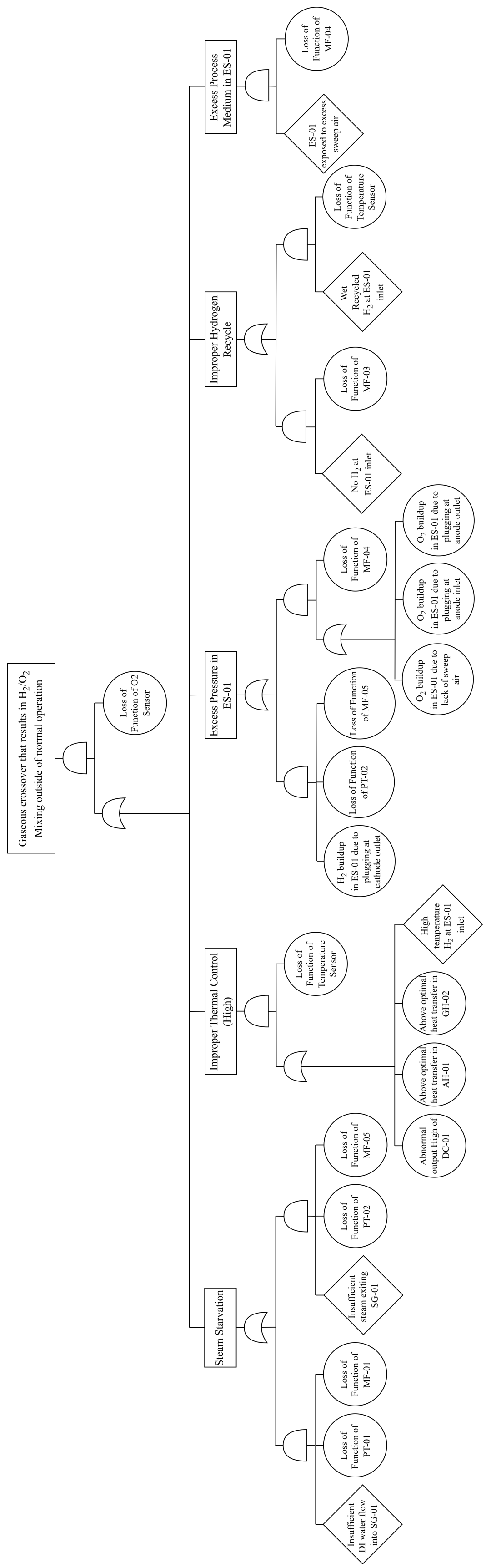

Figure 5.6: Overview of the oxygen and hydrogen mixing fault tree for outside of normal operating conditions

Rank	Cut Set	Order
1	ES-01 Excess Sweep Air · MF-04 Fail to Operate · OS-01 Fail to Operate	3
2	Oxygen buildup due plugging at outlet of ES-01 · MF-04 Fail to Operate · OS-01 Fail to Operate	3
3	Oxygen buildup due plugging at inlet of ES-01 · MF-04 Fail to Operate · OS-01 Fail to Operate	3
4	Oxygen buildup in ES-01 due to lack of sweep air · MF-04 Fail to Operate · OS-01 Fail to Operate	3
5	Wet H_2 in ES-01 · Temperature Sensor Fail to Operate · OS-01 Fail to Operate	3
6	High temperature H_2 at ES-01 inlet · Temperature Sensor Fail to Operate · OS-01 Fail to Operate	3
7	No H_2 at ES-01 inlet · MF-03 Fail to Operate · OS-01 Fail to Operate	3
8	AH-01 Above Optimal Heat Transfer · Temperature Sensor Fail to Operate · OS-01 Fail to Operate	3
9	GH-02 Above Optimal Heat Transfer · Temperature Sensor Fail to Operate · OS-01 Fail to Operate	3
10	DC-01 Abnormal Output High · Temperature Sensor Fail to Operate · OS-01 Fail to Operate	3
11	H_2 buildup due to plugging at outlet of ES-01 · PT-02 Fail to Operate · MF-05 Fail to Operate · OS-01 Fail to Operate	4
12	SG-01 produces insufficient steam · PT-02 Fail to Operate · MF-05 Fail to Operate · OS-01 Fail to Operate	4
13	Insufficient DI water flow into SG-01 · PT-01 Fail to Operate · MF-01 Fail to Operate · OS-01 Fail to Operate	4

Table 5.5: Minimal cut sets of the Oxygen and Hydrogen Mixing fault tree

5.3.6 Release of Nitrogen Outside of Normal Operation

Based on the discussions with INL system operators, nitrogen is used exclusively during startup, shutdown and standby operations. Therefore, a nitrogen release and the potential for asphyxiation would only be of concern outside of normal operation. The constructed fault tree is presented in Figure 5.7 and the minimal cut sets are given in Table 5.6. All 10 of the minimal cut sets are order 2, which means the occurrence of a release of nitrogen requires a failure of the air detection sensor in combination with a leak or rupture of a component.

Rank	**Cut Set**	**Order**
1	MF-02 Leak · AT-01 Fail to Operate	2
2	Pipes and Fittings Leak · AT-01 Fail to Operate	2
3	Valves Leak · AT-01 Fail to Operate	2
4	V-02 Leak · AT-01 Fail to Operate	2
5	V-03 Leak · AT-01 Fail to Operate	2
6	MF-02 Rupture · AT-01 Fail to Operate	2
7	Pipes and Fittings Rupture · AT-01 Fail to Operate	2
8	Valves Rupture · AT-01 Fail to Operate	2
9	V-02 Rupture · AT-01 Fail to Operate	2
10	V-03 Rupture · AT-01 Fail to Operate	2

Table 5.6: Minimal cut sets of the Nitrogen Release fault tree

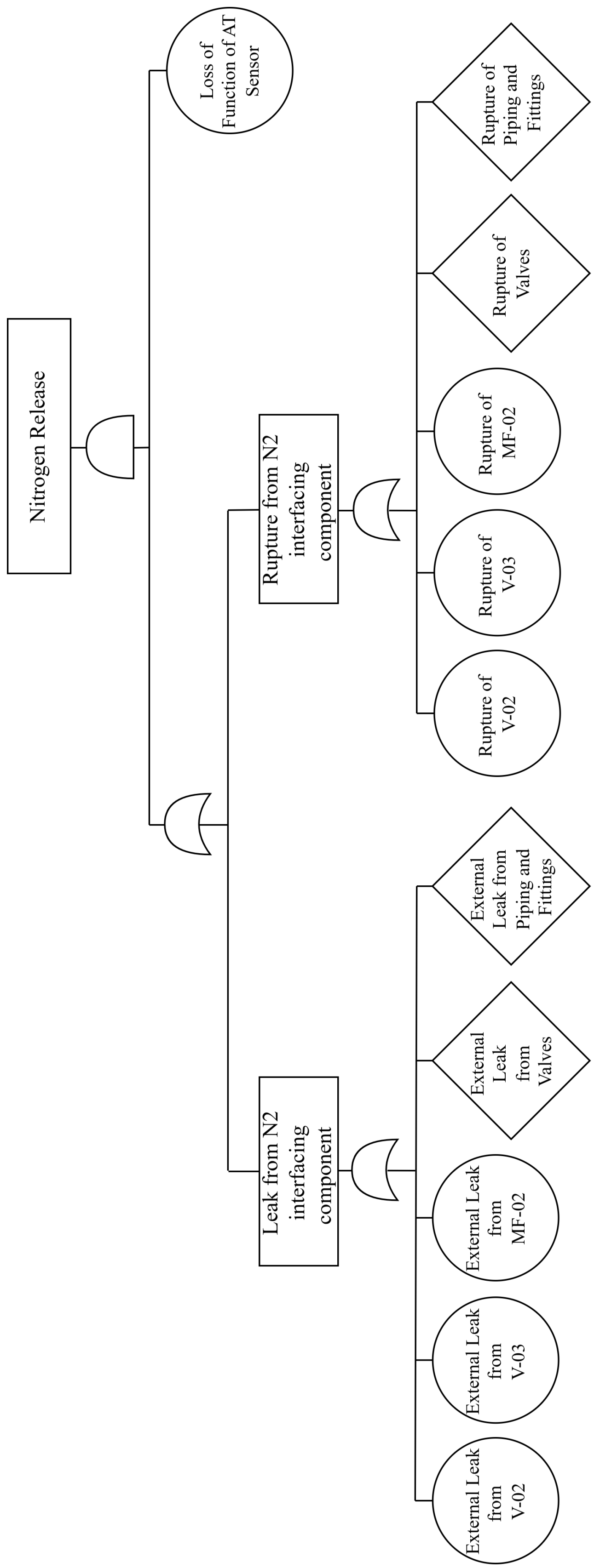

Figure 5.7: Overview of the nitrogen release fault tree for outside of normal operating conditions

5.4 Discussion and Conclusions

5.4.1 Insights from the Hydrogen Release Fault Trees and Minimal Cut Sets

We identified two sources of leaks of a 95% steam, 5% hydrogen mixture. Insufficient seals between components and pipe segments that contain at most 5% hydrogen by volume can release this small amount of hydrogen into the facility. A release of this mixture can also caused by a leak from a component that contains 5% hydrogen by volume. An external leak from GH-01, WT-01, and the various sensors would release a small amount of the mixture. The group of components that make up the water trap system can leak water, which creates an insufficient water seal and provides a pathway for the mixture to leak into the facility.

Similarly, we identified three sources of a minor hydrogen release: an insufficient seal between components, a leak from a component within Functional Group 4, and a separation of components. Insufficient seals between components that interact with hydrogen provide a direct path for escape and accumulate within the facility. A leak from any component in Functional Group 4 or an external leak from the electrolyzer stack can also release hydrogen. A failure mode of note is the decoupling of probe temperature sensors TT-05 and TT-06 from the furnace and electrolyzer stack, respectively. Due to the small size of these sensors and their respective couplings, a small amount of hydrogen has the potential to be released. Hydrogen released from TT-06 would escape into the furnace and be vented outside of the facility. Meanwhile, the hydrogen released from TT-05 would escape into the facility.

The cause of a major hydrogen release stems from either a separation of components or excessive pressure in components in the hydrogen recycle loop. Complete separation of components in Functional Group 4 result in the exposure of 100% of the cross-sectional area and the release hydrogen into the facility. A rupture of water from the water trap subsystem located on the PH-6 line would provide a direct path for compressed pure hydrogen to escape. Additionally, excessive pressure in either the hydrogen recycle tank (V-01) or the hydrogen compressor (CO-01) has the potential to result in a rupture of these components and a release of a large quantity of hydrogen.

In total, we identified 51 minimal cut sets that lead to one of the three types of hydrogen release, 31 of which were second order cut sets. The fault tree structures presented in Figures 5.2, 5.3, and 5.4 highlight the importance of having a reliable hydrogen detection system. The failure of the hydrogen detection sensor in the system results in multiple component and failure mode pairs going undetected and releasing some volume of hydrogen into the facility. Hydrogen is flammable in air at concentrations as low as 4% [51], which results in the release of a small amount of hydrogen evolving into a fire or explosion in the presence of an ignition source. Aside from a release of hydrogen, we constructed one other fault tree for the occurrence of a system failure during normal operation that would result in system downtime and lost hydrogen production.

5.4.2 Insights from the Membrane Degradation Fault Tree and Minimal Cut Sets

Membrane degradation stems from multiple sources throughout the electrolyzer system. We identified five sources of membrane degradation: steam starvation, above-optimal thermal operating conditions, excess pressure in the electrolyzer stack, improper hydrogen recycling, and excess process medium present in the electrolyzer stack. Steam starvation of the electrolyzer stack occurs when there is insufficient steam present in the cathode or fuel electrode. This poses serious concerns for the longevity of the electrolyzer stack due to the potential for electrochemical imbalances to occur in the membrane. Ghezel-Ayagh [21] discussed that steam starvation of their SOE cells resulted in significant delamination of the electrodes that increases the cell voltage well beyond the safe operating limits. Additionally, SOECs are designed to operate at high temperatures, which requires a robust material selection. However, significant deviation from optimal operating conditions has the potential to accelerate the degradation experienced by the membrane. A study by Sassone et al. [46] revealed that degradation rates increase as operating temperatures increase when comparing aging results to the 750 °C reference temperature. Prolonged exposure to the process mediums at significantly high temperatures can thermally stress the electrolyzer stack's membrane, electrodes, and internal seals resulting in this type of system failure [52].

Overpressure caused by the buildup of a process medium in the electrolyzer stack can contribute to membrane degradation that would render the stack ineffective and require a complete replacement. Delamination of the anode electrode has been attributed to the penetration of oxygen gas into defects at the interface between the electrode and electrolyte [11, 53]. A high internal pressure of oxygen in the area of the electrolyte close to the anode electrode is another cause of delamination. This significantly impacts the performance of the electrolyzer stack due to the increased resistance and decreased current density as a result of the lost active surface area at the electrode-electrolyte interface [11]. In time, this will reduce the production rate of hydrogen gas to inoperable efficiencies and require stack replacement.

A unique operating condition of SOECs is the need for hydrogen gas at the inlet of the electrolyzer stack. The presence of hydrogen at the inlet ensures favorable reaction kinetics and slows the migration of nickel in the cathode electrode [12]. We identified improper hydrogen recycling as one of the causes of membrane degradation. One form of improper hydrogen recycling is the loss of hydrogen at the inlet of the electrolyzer stack. The other form of improper hydrogen recycling is when the recycled hydrogen is improperly dried. Residual liquid water could condense onto the electrode, which will decrease the hydrogen production and increase the resistance across the electrolyzer stack.

Similarly, excess steam at the inlet to the electrolyzer stack negatively impacts the structural stability of nickel-based cathode electrodes [11]. The increased amounts of steam are attributed to the erratic output, tending high, or abnormal output high of the steam generator. Both failure modes would result in the steam generator producing more steam than intended, which can degrade the cathode electrode. Additionally, the anode electrode will face similar problems when exposed to excess sweep air during operation. Depending on the operating mode (Galvanostatic or Potentio-Galvanostatic), as the flow rate of sweep air increases the degradation rate of the stack has been shown to increase [47]. The sweep air has the potential to carry species such as chromium, boron, and sulfur [11]. These species originate from the steel alloy interconnects used in the stack, the glass sealant, and the sweep air, respectively. The subsequent chemical reactions between the electrode and these species contribute to the degradation of the oxygen electrode and reduce the longevity of the electrolyzer stack [54].

In summary, the fault tree structure in Figure 5.5 showcased specific combinations of failures of the SOE system that contribute to the occurrence of membrane degradation. This system failure can be mitigated by ensuring the reliability of the DI water supply, appropriate thermal and pressure control in ES-01, proper hydrogen recycling, and accurate control over the volumes of process medium entering ES-01. Additionally, the key safety and control system components include the mass flow controllers, various temperature transmitters, and two of the pressure transmitters. Eight out of the 13 second order cut sets have the failure to operate of a mass flow controller as one of the two components necessary for this system failure to manifest. The other five second-order cut sets include the failure of various temperature sensors throughout the system. These insights substantiate the need for proper placement of these sensors throughout the SOE system.

5.4.3 Insights from the Hydrogen and Oxygen Mixing Fault Tree and Minimal Cut Sets

The hydrogen and oxygen mixing fault tree, shown in Figure 5.6, has a similar structure to the membrane degradation fault tree. The key differences are the inclusion of OS-01 failing to operate, the exclusion of above optimal heat transfer of the furnace, and the exclusion of excess steam at the inlet of ES-01. During startup or shutdown, the furnace will not be at a constant temperature. Therefore, above optimal heat transfer would either slow system cool down or quicken system startup rather than manifest in gaseous crossover. Similarly, in startup and shutdown, nitrogen and hydrogen are flushed through the electrolyzer stack, which means that excessive steam is not a possible failure that can occur. The cut sets of this fault tree are also similar to those of the Membrane Degradation fault tree. For this top event, the cut sets are either third order or fourth order and highlight the importance of the in-line oxygen detector in the PH-7 pipe segment in addition to the mass flow controllers and temperature transmitters. Oxygen detection sensors will be able to detect large quantities of oxygen mixed in with hydrogen and prevent the accumulation of a flammable mixture that can lead to a fire.

5.4.4 Insights from the Nitrogen Release Fault Tree and Cut Sets

The nitrogen release fault tree structure consists of either leaks or rupture of nitrogen components, which pose an asphyxiation hazard to facility personnel. All 10 minimal cut sets are second order and involve the failure of the air detection system in the facility. This feature of the safety and control system is critical to ensuring that abnormal quantities of nitrogen in the environment can be detected because the gas is odorless, colorless, and tasteless. Nitrogen is also slightly heavier than air, so it has a tendency to settle, which requires this part of the safety and control system to be placed in its proper locations in the facility. Ensuring the safety of facility personnel is an integral part of the safe and reliable operation of SOE facilities.

5.4.5 Conclusions

This chapter provides engineers working on early-stage deployments with important insights into critical failure modes and safety and control system features that are required to ensure the safe and reliable operation of an SOE facility. These areas include the DI water supply, proper control of stack operating parameters, and proper hydrogen recycling. Due to the uniqueness of the SOE stack, including a hydrogen recycle loop adds both complexity and new risks to operating electrolysis systems. The recycle loop is an area where failures can contribute to hydrogen releases, membrane degradation, or the presence of a flammable mixture of hydrogen and oxygen. Without the proper DI water supply (in a stand-alone system) or steam supply (in a system coupled to an NPP), the electrolyzer stack will experience damage. This results in both system downtime and high capital costs to replace the stack. The development of fault tree structures at a high level of abstraction has enabled us to pinpoint key features of the safety and control system and name key areas of the system that contribute to specific undesired system failures.

Chapter 6: Summary, Contributions and Opportunities for Future Work

6.1 Summary of Research and Contributions

We documented the current state of the art of SOE technology and risk modeling by conducting a literature review. In reviewing the literature, we identified multiple challenges to the continued development of SOE technologies, including the lack of attention given to the balance of plant and its influence on electrolyzer stack safe and reliable operation. Rather, current research focused on the material properties, material selection and improving the performance and efficiency of electrolyzer stacks. Additionally, reports that discussed integration strategies for hydrogen-nuclear sites primarily focused on the design of heat extraction systems. Meanwhile, the limited risk analyses for hydrogen-nuclear integration took a conservative approach by focusing exclusively on the risks posed by hydrogen explosions on the NPP. The work presented in this thesis addressed the gap of a lack of well documented insights on critical failure modes and risk scenarios that result in various undesired system failures, including hazardous releases of gas and severe membrane degradation for SOE facilities.

By reviewing and synthesizing the literature, we were able to select and modify a publicly available SOE facility design to more accurately reflect design elements required in large scale containerized facilities. Using the P&ID provided in [16] as a basis, we defined a new system boundary, all necessary safety and control systems including associated trigger states and complied the relevant system operating conditions. We established a 25 kW SOE facility design with all of the necessary information to inform future QRA and aid in the scalability of key insights to commercial system designs. We rigorously documented our approach to conduct the FMEA, including the development of the system reference guide and the engineering team's approach to performing the FMEA across a 6 month time frame. Through the FMEA process, we identified relevant component failure modes and developed 650 risk scenarios for the SOE system. Then, we leveraged the set of failure modes to construct fault trees for various system failures. These fault tree structures created the system failure understanding and logic, identified the combinations of critical failure modes and pinpointed the important safeguards within the safety and control system.

This thesis contributes to the state of knowledge surrounding potential failures in SOE systems in the following ways:

- **Contribution 1: SOE Facility Failure Modes and Causes**. The development of a comprehensive set of relevant failure modes, for over 80 components of an SOE facility spanning water supply and steam generation, electrolysis stack, oxygen processing and production, hydrogen production and recycle and additional critical functional groups. Through the FMEA process, we also qualitatively evaluated the likelihood of occurrence and severity of each component failure mode to classify the risk posed to the overall SOE system. For each component and its failure modes, we provide the number of high and medium risk-scenarios.

- **Contribution 2: Critical Risk Scenarios List for an SOE Facility**. We synthesize a list of the 65 most critical risk scenarios from over 650 risk scenarios we identified. These critical risk scenarios apply to an SOE facility both during normal operation and outside of normal operation. We have provided a readily available record of critical scenarios, which are fully discussed and elaborated upon within the FMEA documentation.

- **Contribution 3: Basis for QRA for an SOE Facility**. We created system failure understanding and logic that provide the foundation for QRAs needed to establish the regulatory foundations to ensure the safe and reliable deployment of solid oxide electrolysis. We developed fault trees to identify combinations of critical component failures and visually display the relevant component failure modes that result in specific undesired system failures which can pose undue risk as a basis for subsequent quantification in QRA.

6.2 Publications and Presentations

6.2.1 Peer-reviewed Journal Publications

One journal paper that will synthesize the methods and results of Chapter 4 is being prepared for submission. Over the course of my studies, an additional two peer-reviewed journal publications were developed that identify and address key gaps within hydrogen risk and reliability. The following are the peer-reviewed journal publications:

- **In Progress**
  - V. Grabovetska, S.E. Wismer, A. Al-Douri, K.M. Groth, ”SOE Facility Failure Scenarios Identified by Failure Modes and Effects Analysis (FMEA)” [*Manuscript in preparation*]
- **Completed**

- S.E. Wismer, A. Jimenez, A. Al-Douri, V. Grabovetska, and K. M. Groth, “PEM Electrolyzer Failure Scenarios Identified by Failure Modes and Effects Analysis (FMEA).” In: *International Journal of Hydrogen Energy*, vol. 89, pp. 1280-1289, Nov. 2024, doi: 10.1016/j.ijhydene.2024.09.397. [36]
- R. Yang, C. A. Schell, A. Ruiz-Tangle, V. Grabovetska, A. J. Gupta and K. M. Groth, “Research gaps in quantitative risk assessment (QRA) of hydrogen transmission pipelines” In: *International Journal of Hydrogen Energy*, vol. 71, pp. 916-929, May 2024, doi: 10.1016/j.ijhydene.2024.05.281. [55]

6.2.2 Reports and Presentations

In addition to the expected peer-reviewed journal publications, I collaborated on one workshop report and two presentations. Attending these workshops enabled feedback and engagement that led to deeper knowledge and connections leveraged in this work.

- K. M. Groth, A. Ruiz, V. Grabovetska and L. M. Reising, “Hydrogen Systems Risk and Reliability Workshop Proceedings Report” Center for Risk and Reliability, University of Maryland, Nov. 2024. [14]
- V. Grabovetska, S. E. Wismer, K. M. Groth, “Failure Modes and Effects Analysis of a Solid Oxide Electrolyzer System for Hydrogen Production at Nuclear Power Plants” Vertical Flight Society Meeting, University of Maryland, College Park, October 2024. [56]
- V. Grabovetska, S. E. Wismer, K. M. Groth, “Failure Modes and Effects Analysis of a Solid Oxide Electrolyzer System for Hydrogen Production at Nuclear Power Plants” Hydrogen

Systems Risk and Reliability Workshop, University of Maryland, College Park, September 2024. [57]

6.3 Opportunities for Future Work

As electrolysis technologies continue to develop and mature, the ways in which these complex engineered systems can fail will also continue to evolve. This section presents opportunities for future work to continue to advance our understanding of the risk and reliability of high temperature electrolysis technology.

For early deployments of SOE technology, the next immediate step would be to reform the list of the 65 critical risk scenarios identified via the FMEA into a practical document for the industry. The critical risk scenarios can be transformed into a checklist that can be utilized by engineers and operators in an effort to identify and mitigate risk scenarios that may arise. This will also provide further opportunity to validate the risk scenarios we have identified and promote the dissemination of the common failures the industry may be experiencing.

The main direction for near-term future work is to complete the QRA based on this current work. With the high-level failure logic established, expanding the fault tree structures allows for the subsequent quantification of the frequency of occurrence of undesired system failures. Taking the analysis a step further to include the quantitative evaluation of the fault tree structures would answer the next question of risk analysis: how likely is it to happen? While there is still a lack of hydrogen specific component failure data, using the best available data provides a reasonable estimate of the frequency which can be used in the decision-making process for siting requirements of SOE at NPPs. Completing the quantitative fault tree analysis also results in identifying the risk-significant components via importance measure analysis. Additionally, it may be beneficial to consider human errors in the fault tree analysis since the literature has identified human error as a contributor to SOE system failure. The final steps of the QRA process would be to further develop the risk scenarios through event sequence diagrams and characterize the damage consequences using simulation tools.

Long-term future work should include using the aforementioned QRA as a basis for integrated SOE facility designs which include sufficiently detailed component information on the electrical and thermal tie-in to an NPP. Currently, the U.S Department of Energy and INL have begun to develop preliminary designs for the heat extraction system that would be housed on the nuclear island. However, limited work is available on the exact components and safety and control systems required to integrate these complex facilities. In order to meet domestic and global demands for clean hydrogen, future work must fully understand and quantify the potential risks that may arise when siting commercial scale solid oxide electrolysis facilities at nuclear power plants.

6.4 Broader Research Impact

As domestic and global efforts increase their focus on the transition to renewable energy, clean hydrogen produced from water electrolysis coupled to a clean source of electricity will play a crucial role. We anticipate the results of this work to impact both the hydrogen and nuclear industries. By providing a comprehensive list of failure modes, causes and consequences for an SOE facility through the use of a well-documented analysis process, we established critical insights for early deployment decisions and built the foundations to inform future QRAs for

SOE. As hydrogen technologies continue to mature, documenting the methodology, approach and providing a detailed design becomes critical to the scalability of these insights from our test-bed SOE design to commercial systems. We envision that this set of failure modes and causes will serve as a basis, from which QRAs of commercial SOE facilities build upon. The list of 65 critical risk scenarios that can occur in an SOE facility provide early deployments with a practical guide for identifying the evolution of a consequence both during and outside of normal operation. Lastly, we established system failure understanding and logic to provide the foundation for a QRA of this SOE facility. The combinations of critical component failures present early stage deployments with targeted areas of the SOE system to focus their engineering efforts. Ultimately, the quantification of these results will provide valuable layout and siting recommendations and establish risk-informed regulatory foundations that will ensure the safe and reliable deployment of SOE technologies at NPPs.

Appendix

A complete enumeration of the FMEA results on a modal level. The results are divided by functional group.

Functional Group 1: DI Water and Steam Generation

Component ID	Component	Component Description	Component Function	Failure Mode	Likelihood of Occurrence (L)	Consequences of Failure Mode	Operation State	Current Controls and Safeguards	Severity (S)	Risk (R = L x S)
HV-01	**Hand Valve**	**Hand Valve**	**Can be closed to separate the system from the DI water supply**	**Bent/warped/damaged**	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**
				Contamination	**Unlikely**	Debris from degradation of the inside of the component can travel through the water processing and steam generation functional group and embed in the membrane of ES-01. This can cause irreversible damage to the membrane. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05**	**Catastrophic**	**High**
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing and steam generation functional group and embed in the membrane of ES-01. Which can cause damage to the membrane. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01***	**Catastrophic**	**High**
				Full Freezing	**Unlikely**	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**
				Partial Freezing	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**
				Full Plugging	**Unlikely**	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**
				Partial Plugging	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**

				External Leak of Process Medium (Water)	**Remote**	Water leakage has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Water)	**Unlikely**	Loss of water has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, WS-01, O2-01***	**Catastrophic**	**High**
HV-02	**Hand Valve**	**Hand Valve**	**Can be closed to separate the system from the DI water supply**	**Bent/warped/damaged**	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-02. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-02. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**
				Contamination	**Unlikely**	Debris from degradation of the inside of the component can travel through the water processing and steam generation functional group and embed in the membrane of ES-01. This can cause irreversible damage to the membrane. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05**	**Catastrophic**	**High**
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing and steam generation functional group and embed in the membrane of ES-01. Which can cause damage to the membrane. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01***	**Catastrophic**	**High**
				Full Freezing	**Unlikely**	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**
				Partial Freezing	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-02. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-02. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**
				Full Plugging	**Unlikely**	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**

					Unlikely	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-01, MF-05, O2-01*, WS-01	Catastrophic	High
				Partial Plugging	Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-02. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	Normal	MF-01, O2-01, MF-05, WS-01	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-02. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-01, MF-05, O2-01*, WS-01	Catastrophic	High
				External Leak of Process Medium (Water)	Remote	Water leakage has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	Normal	MF-01, O2-01, MF-05, WS-01	Catastrophic	Medium
					Remote	Water leakage has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-01, MF-05, WS-01, O2-01*	Catastrophic	Medium
				External Rupture of Process Medium (Water)	Unlikely	Loss of water has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	Normal	MF-01, O2-01, MF-05, WS-01	Catastrophic	High
					Unlikely	Loss of water has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-01, MF-05, WS-01, O2-01*	Catastrophic	High
BPR-01	Back Pressure Regulator	Back Pressure Regulator	Maintains defined pressure upstream of it's own inlet and continually adjusts to maintain the desired upstream pressure.	Bent/warped/damaged	Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around BPR-01.There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	Normal	MF-01, O2-01, MF-05, WS-01	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around BPR-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-01, MF-05, O2-01*, WS-01	Catastrophic	High
				Contamination	Unlikely	Debris from degradation of the inside of the component can travel through the water processing and steam generation functional group and embed in the membrane of ES-01. This can cause irreversible damage to the membrane. This causes facility downtime to replace the stack.	Normal	MF-01, O2-01, MF-05	Catastrophic	High
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing and steam generation functional group and embed in the membrane of ES-01. Which can cause damage to the membrane. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-01, MF-05, O2-01*	Catastrophic	High
				Full Freezing	Unlikely	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	Normal	MF-01, O2-01, MF-05, WS-01	Catastrophic	High
					Unlikely	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-01, MF-05, O2-01*, WS-01	Catastrophic	High

				Partial Freezing	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around BPR-01.There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around BPR-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**
				Full Plugging	**Unlikely**	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**
				Partial Plugging	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around BPR-01.There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around BPR-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**
				Abnormal output-high	**Remote**	Flow of excess water into SG-01 can cause less water to be heated into steam. Steam is at a lower temperature then the desired 800C, which can cause a higher then intended differential temperature between the stack and the process medium. This results in membrane degradation of ES-01. Over time, this can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-02, TT-03, TT-04A**	**Catastrophic**	**Medium**
				Abnormal output-low	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around BPR-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around BPR-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**
				Fail Open	**Remote**	Flow of excess water into SG-01 can cause less water to be heated into steam. Steam is at a lower temperature then the desired 800C, which can cause a higher then intended differential temperature between the stack and the process medium. This results in membrane degradation of ES-01. Over time, this can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-02, TT-03, TT-04A**	**Catastrophic**	**Medium**
				Fail Closed	**Unlikely**	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01*, WS-01**	**Catastrophic**	**High**
				External Leak of Process Medium (Water)	**Remote**	Water leakage has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**Medium**

					Remote	Water leakage has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Water)	**Unlikely**	Loss of water has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, WS-01, O2-01***	**Catastrophic**	**High**
PT-01	**Pressure Sensor**	**Pressure Sensor**	**Measures and transmits pressure in PW-1**	**External Leak of Process Medium (Water)**	**Remote**	Water leakage has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Water)	**Unlikely**	Loss of water has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, WS-01, O2-01***	**Catastrophic**	**High**
NV-01	**Needle Valve**	**Needle Valve**	**Fine flow control of water into the inlet of the mass flow controller and steam generator.**	**Bent/warped/damaged**	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around NV-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around NV-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01***	**Catastrophic**	**High**
				Contamination	**Unlikely**	Debris from degradation of the inside of the component can travel through the water processing and steam generation functional group and embed in the membrane of ES-01. This can cause irreversible damage to the membrane. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05**	**Catastrophic**	**High**
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing and steam generation functional group and embed in the membrane of ES-01. Which can cause damage to the membrane. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01***	**Catastrophic**	**High**
				Full Freezing	**Unlikely**	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05**	**Catastrophic**	**High**
					Unlikely	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01***	**Catastrophic**	**High**

				Partial Freezing	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around NV-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around NV-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01***	**Catastrophic**	**High**
				Full Plugging	**Unlikely**	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05**	**Catastrophic**	**High**
					Unlikely	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01***	**Catastrophic**	**High**
				Partial Plugging	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around NV-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around NV-01. There is a potential for water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01***	**Catastrophic**	**High**
				Abnormal output-high	**Remote**	Flow of excess water into SG-01 can cause less water to be heated into steam. Steam is at a lower temperature then the desired 800C, which can cause a higher then intended differential temperature between the stack and the process medium. This results in membrane degradation of ES-01. Over time, this can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-02, TT-03, TT-04A**	**Catastrophic**	**Medium**
				Abnormal output-low	**Unlikely**	Loss of sufficient water flow can cause strain to SG-01 potentially causing overheating/failure. This results in insufficient steam production, which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05**	**Catastrophic**	**High**
					Unlikely	Loss of sufficient water flow can cause strain to SG-01 potentially causing overheating/failure. This results in insufficient steam production, which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01***	**Catastrophic**	**High**
				Erratic Output - tends high	**Remote**	Flow of excess water into SG-01 can cause less water to be heated into steam. Steam is at a lower temperature then the desired 800C, which can cause a higher then intended differential temperature between the stack and the process medium. This results in membrane degradation of ES-01. Over time, this can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-02, TT-03, TT-04A**	**Catastrophic**	**Medium**
				Fail Open	**Remote**	Flow of excess water into SG-01 can cause less water to be heated into steam. Steam is at a lower temperature then the desired 800C, which can cause a higher then intended differential temperature between the stack and the process medium. This results in membrane degradation of ES-01. Over time, this can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-02, TT-03, TT-04A**	**Catastrophic**	**Medium**
				Fail Closed	**Unlikely**	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05**	**Catastrophic**	**High**
					Unlikely	Total obstruction of water flow causes water starvation of SG-01 which leads to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, O2-01***	**Catastrophic**	**High**

				External Leak of Process Medium (Water)	**Remote**	Water leakage has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Water)	**Unlikely**	Loss of water has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-01, O2-01, MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-01, MF-05, WS-01, O2-01***	**Catastrophic**	**High**
MF-01	**Mass Flow Meter**	**Mass Flow Meter**	**Measures and transmits flow rate of PW-1**	**External Leak of Process Medium (Water)**	**Remote**	Water leakage has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**O2-01, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Water)	**Unlikely**	Loss of water has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**O2-01, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause water starvation of SG-01 which can lead to steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**High**
SG-01	**Steam Generator**	**Steam Generator**	**Water flows into the generator where an electrical heating element heats the water to steam at a temperature of at least 800C**	**Bent/warped/damaged**	**Unlikely**	Insufficient seal with PH-1. Direct path for a minor H2 release if H2 can overcome force of steam exiting SG-01.	**Normal**	**H2-01**	**Serious**	**Medium**
					Unlikely	Insufficient seal with PH-1. Sufficient quantities of steam exiting SG-01 do not reach the inlet of ES-01. Over time this could cause steam starvation of ES-01, resulting in potential irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**O2-01, MF-05**	**Catastrophic**	**High**
					Unlikely	Insufficient seal with PH-1. Sufficient quantities of steam exiting SG-01 do not reach the inlet of ES-01. Over time this could cause steam starvation of ES-01, resulting in potential degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05**	**Catastrophic**	**High**
					Unlikely	Insufficient seal with PW-2 causing water to leak from the inlet of SG-01. Due to insufficient inlet water flow, SG-01 experiences strain and has the potential to overheat/fail. This can cause insufficient steam production. This results in steam starvation of ES-01, which can lead to irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	**Normal**	**WS-01, O2-01, MF-05**	**Catastrophic**	**High**
					Unlikely	Insufficient seal with PW-2 causing water to leak from the inlet of SG-01. Due to insufficient inlet water flow, SG-01 experiences strain and has the potential to overheat/fail. This can cause insufficient steam production. This results in steam starvation of ES-01, which can lead to degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**WS-01, MF-05**	**Catastrophic**	**High**

				Contamination	**Unlikely**	Due to insufficient inlet water flow, SG-01 experiences strain and has the potential to overheat/fail. This can cause insufficient steam production. This results in steam starvation of ES-01, which can lead to irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	**Normal**	**O2-01, MF-05**		**Catastrophic**	**High**
					Unlikely	Due to insufficient inlet water flow, SG-01 experiences strain and has the potential to overheat/fail. This can cause insufficient steam production. This results in steam starvation of ES-01, which can lead to degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05**		**Catastrophic**	**High**
				Full Plugging - at Inlet	**Unlikely**	Total Obstruction of water flow into SG-01 can cause steam starvation of ES-01. This can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. This causes facility downtime to replace the stack.	**Normal**	**O2-01, MF-05, PT-01***		**Catastrophic**	**High**
					Unlikely	Total Obstruction of water flow into SG-01 can cause steam starvation of ES-01. This can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, PT-01***		**Catastrophic**	**High**
				Partial Plugging - at Inlet	**Unlikely**	Due to insufficient inlet water flow, SG-01 experiences strain and has the potential to overheat/fail. This can cause insufficient steam production. This results in steam starvation of ES-01, which can lead to irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	**Normal**	**O2-01, MF-05, PT-01****		**Catastrophic**	**High**
					Unlikely	Due to insufficient inlet water flow, SG-01 experiences strain and has the potential to overheat/fail. This can cause insufficient steam production. This results in steam starvation of ES-01, which can lead to degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, PT-01****		**Catastrophic**	**High**
				Fail to Operate	**Unlikely**	SG-01 does not produce any steam. ES-01 experiences steam starvation which can lead to irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	**Normal**	**MF-05**		**Catastrophic**	**High**
					Unlikely	SG-01 does not produce any steam. ES-01 experiences steam starvation which can lead to degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, O2-01***		**Catastrophic**	**High**
				Erratic Output - tends high	**Remote**	SG-01 produces excess steam. Steam/H2 ratio is too high. Over time this can cause Nickel depletion/evaporation in the cathode of ES-01. Which results in irreversible membrane degradation of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-05**		**Catastrophic**	**Medium**
				Abnormal output-high	**Remote**	SG-01 produces excess steam. Steam/H2 ratio is too high. Over time this can cause Nickel depletion/evaporation in the cathode of ES-01. Which results in irreversible membrane degradation of ES-01. This causes facility downtime to replace the stack.	**Normal**	**MF-05**		**Catastrophic**	**Medium**
				Abnormal output-low	**Unlikely**	SG-01 produces insufficient quantities of steam. Over time, this could cause steam starvation of ES-01, resulting in irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	**Normal**	**O2-01, MF-05**		**Catastrophic**	**High**
					Unlikely	SG-01 produces insufficient quantities of steam. Over time, this could cause steam starvation of ES-01, resulting in degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05**		**Catastrophic**	**High**
				External Leak of Process Medium (Water)	**Unlikely**	Due to a leakage of water, SG-01 experiences insufficient steam production and strain and has the potential to overheat/fail. This results in steam starvation of ES-01, which can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	**Normal**	**O2-01, MF-05, WS-01**		**Catastrophic**	**High**

					Unlikely	Due to a leakage of water, SG-01 experiences insufficient steam production and strain and has the potential to overheat/fail. This results in steam starvation of ES-01, which can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01	Catastrophic	High
				Internal Leak of Process Medium (Water)	Unlikely	Due to a leakage of water, SG-01 experiences insufficient steam production and strain and has the potential to overheat/fail. This results in steam starvation of ES-01, which can cause irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	Normal	O2-01,MF-05	Catastrophic	High
					Unlikely	Due to a leakage of water, SG-01 experiences insufficient steam production and strain and has the potential to overheat/fail. This results in steam starvation of ES-01, which can cause degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05	Catastrophic	High
				External Rupture of Process Medium (Water)	Unlikely	SG-01 does not produce any steam. ES-01 experiences steam starvation which can lead to irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	Normal	O2-01, MF-05, WS-01	Catastrophic	High
					Unlikely	SG-01 does not produce any steam. ES-01 experiences steam starvation which can lead to degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01	Catastrophic	High
				Internal Rupture of Process Medium (Water)	Unlikely	SG-01 does not produce any steam. ES-01 experiences steam starvation which can lead to irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	Normal	O2-01, MF-05	Catastrophic	High
					Unlikely	SG-01 does not produce any steam. ES-01 experiences steam starvation which can lead to degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05	Catastrophic	High
				Insufficient heat transfer - below optimal	Unlikely	SG-01 produces insufficient quantities of steam. Over time, this could cause steam starvation of ES-01, resulting in irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	Normal	O2-01, MF-05	Catastrophic	High
					Unlikely	SG-01 produces insufficient quantities of steam. Over time, this could cause steam starvation of ES-01, resulting in degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05	Catastrophic	High
PS-01	Power Supply	Power Supply	Provides power to the heating element in SG-01	Fail to Operate	Unlikely	SG-01 does not produce any steam. ES-01 experiences steam starvation which can lead to irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	Normal	O2-01, MF-05	Catastrophic	High
					Unlikely	SG-01 does not produce any steam. ES-01 experiences steam starvation which can lead to degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05	Catastrophic	High
				Abnormal Output - High	Unlikely	Over time SG-01 experiences strain and has the potential to overheat/fail. This provides insufficient steam to ES-01. This results in potential steam starvation of ES-01, which can lead to irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	Normal	O2-01, MF-05	Catastrophic	High
					Unlikely	Over time SG-01 experiences strain and has the potential to overheat/fail. This provides insufficient steam to ES-01. This results in potential steam starvation of ES-01, which can lead to degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05	Catastrophic	High
				Abnormal Output - Low	Unlikely	ES-01 does not receive sufficient steam from SG-01. Over time this could cause steam starvation of ES-01, resulting in potential irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This causes facility downtime to replace the stack.	Normal	O2-01, MF-05	Catastrophic	High
					Unlikely	ES-01 does not receive sufficient steam from SG-01. Over time this could cause steam starvation of ES-01, resulting in potential degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	O2-01, MF-05	Catastrophic	High

Condenser Line										
GV-01	Gate Valve	Gate Valve	Valve this is normally open during normal operation to provide a small amount of fluid flow through the condensers	Bent/warped/damaged	Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-01. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-01. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-01. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-01. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Contamination	Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Full Freezing	Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High

				Partial Freezing	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-01. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-01.This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-01. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-01.This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
				Full Plugging	**Unlikely**	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
				Partial Plugging	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-01. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-01. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-01. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**

					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-01.This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
				External Leak of Process Medium (Water)	**Remote**	Water leakage has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Water)	**Unlikely**	Loss of water has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**High**
HV-07	**Hand Valve**	**Hand Valve**	**Normally open during operation and provides continuous flow of DI water to the condenser**	**Bent/warped/damaged**	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**

				Contamination	**Unlikely**	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
				Full Freezing	**Unlikely**	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
				Partial Freezing	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07.This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07.This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**

				Full Plugging	**Unlikely**	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
				Partial Plugging	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07.This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07.This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
				External Leak of Process Medium (Water)	**Remote**	Water leakage has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Water)	**Unlikely**	Loss of water has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**High**

					Unlikely	Loss of water has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
HV-08	Hand Valve	Hand Valve	Normally open during normal operation and provides continuous DI water to the condenser	Bent/warped/damaged	Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-08. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-08. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-08. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-07. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Contamination	Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Full Freezing	Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High

					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack. .	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Partial Freezing	Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-08. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-08.This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-08. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-08.This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Full Plugging	Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Partial Plugging	Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-08. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-08.This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High

					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-08. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-08.This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				External Leak of Process Medium (Water)	Remote	Water leakage has the potential to cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	Medium
				External Rupture of Process Medium (Water)	Unlikely	Loss of water has the potential to cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
HV-09	Hand Valve	Hand Valve	Normally open during normal operation and provides continuous flow of DI water to the condenser	Bent/warped/damaged	Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-09. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-09. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-09. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High

					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-09. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Contamination	Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Full Freezing	Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Partial Freezing	Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-09. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-09.This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High

					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-09. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-09.This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Full Plugging	Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Partial Plugging	Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-09. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-09.This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-09. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-09.This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				External Leak of Process Medium (Water)	Remote	Water leakage has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	Medium

					Remote	Water leakage has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	Medium
				External Rupture of Process Medium (Water)	Unlikely	Loss of water has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
HV-10	Hand Valve	Hand Valve	Normally open during normal operation and provides continuous flow of DI water to the condenser	Bent/warped/damaged	Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-10. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-10. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-10. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-10. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Contamination	Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High

					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Debris from degradation of the inside of the component can travel through the water processing functional group and clog the condensers. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Full Freezing	Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Partial Freezing	Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-10. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-10.This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-10. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-10.This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Full Plugging	Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High

					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to no water in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
				Partial Plugging	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-10. This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-10.This leads to an insufficient water level in the condensers, which can cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-10. This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around HV-10.This leads to an insufficient water level in the condensers, which can cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
				External Leak of Process Medium (Water)	**Remote**	Water leakage has the potential to cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Water)	**Unlikely**	Loss of water has the potential to cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**High**

					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
Condenser	Condenser	Condenser	Passive Component -- Cools H2 gas using DI water that sits in the condenser and chilled water running through the tubes.	Leak Utility Medium (DI Water)	Unlikely	Insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Insufficient water level in the condensers, which can cause insufficient cooling of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
HV-11	Hand Valve	Hand Valve	Connects DI water flow from condensers to a drain	Full Freezing	Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Full Plugging	Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				External Leak of Process Medium (Water)	Remote	Water leakage has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	Medium

					Remote	Water leakage has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Water)	**Unlikely**	Loss of water has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**High**
CV-04	**Check Valve**	**Check Valve**	**Prevents backflow of DI water from the drain into the Condenser**	**Full Freezing**	**Unlikely**	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
				Full Plugging	**Unlikely**	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-08A/B/C/D, TT-09, TT-10, O2-01***	**Catastrophic**	**High**
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-08A/B/C/D, TT-09, TT-10**	**Catastrophic**	**High**

					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				Fail Closed	Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause accelerated crossover. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-08A/B/C/D, TT-09, TT-10	Catastrophic	High
					Unlikely	Total obstruction to water flow leads to water stagnation in the condensers, which can cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-08A/B/C/D, TT-09, TT-10, O2-01*	Catastrophic	High
				External Leak of Process Medium (Water)	Remote	Water leakage has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	Medium
				External Rupture of Process Medium (Water)	Unlikely	Loss of water has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficient drying of the produced H2 gas. Wet H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
						H2 RECYCLE LINE				
SV-03	Solenoid Valve	Solenoid Valve	Drains water from WT-02 when LI-02 signals high water level and closes when LI-02 signals low so ensure some water is always left in WT-02	External Leak Process Medium (Water)	Unlikely	Leak of water from SV-03 which can cause an insufficient water seal. This results in a pathway for minor H2 release to the environment.	Normal	WS-01, H2-01, MF-05	Catastrophic	High

				Fail Open	Unlikely	All water in WT-02 exist from SV-03 which causes no water seal to be present. This leads to a major release of H2 to the environment.	Normal	WS-01, H2-01, MF-05	Catastrophic	High
				Fail to Close	Unlikely	All water in WT-02 exist from SV-03 which causes no water seal to be present. This leads to a major release of H2 to the environment.	Normal	WS-01, H2-01, MF-05	Catastrophic	High
				External Rupture of Process Medium (Water)	Unlikely	Rupture of water from SV-03 which causes no water seal to be present. This leads to a major release of H2 to the environment.	Normal	WS-01, H2-01, MF-05	Catastrophic	High
WT-02	Water Trap	Water Trap	Collects excess water from PH-7.	External Leak of Process Medium (Water)	Unlikely	Leak of water from WT-02 which can cause an insufficient water seal. This results in a pathway for a minor H2 release to the environment.	Normal	H2-01, LI-02, WS-01, MF-05	Catastrophic	High
				External Leak of Process Medium (H2)	Unlikely	A leak from WT-02 results in an minor release of H2 to environment.	Normal	H2-01, MF-05	Catastrophic	High
				External Rupture of Process Medium (Water)	Unlikely	Loss of water from WT-02, no water seal is present at the bottom of WT-02. This can cause a major release of H2 into the environment.	Normal	H2-01, LI-02, WS-01, MF-05	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	A rupture of WT-02 results in an major release of H2 to environment.	Normal	H2-01, MF-05	Catastrophic	High
				Bent/warped/damaged	Unlikely	Insufficient seal with piping connecting to PH-6 which can lead to a minor release of H2 into the environment.	Normal	H2-01, MF-05	Catastrophic	High
LI-02	Level Indicator	Level Indicator	Triggers High/Low to acuate SV-03	External Leak of Process Medium (Water)	Unlikely	Leak of water for LI-02 leads to a minor release of H2 into the environment.	Normal	H2-01, WS-01	Catastrophic	High
				External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				External Rupture of Process Medium (Water)	Unlikely	Rupture of water from LI-02 leads to a major release of H2 into the environment.	Normal	H2-01, WS-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01, WS-01	Catastrophic	High
PH-1 LINE										
WT-01	Water Trap	Water Trap	Collects excess water from PH-1.	External Leak of Process Medium (Water)	Unlikely	Leak of water from WT-01 which can cause an insufficient water seal. This results in a minor H2 release to the environment.	Normal	H2-01, LI-01, WS-01	Serious	Medium
				External Leak of Process Medium (H2)	Unlikely	A leak from WT-01 results in an minor release of H2 to environment.	Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (Water)	Unlikely	Loss of water from WT-01, no water seal is present at the bottom of WT-01. This can cause a major release of H2 into the environment.	Normal	H2-01, LI-01, WS-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	A rupture of WT-01 results in an major release of H2 to environment.	Normal	H2-01	Catastrophic	High
				Bent/warped/damaged	Unlikely	Insufficient seal with piping connecting to PW-6 which can lead to a minor release of H2 into the environment.	Normal	H2-01	Serious	Medium
LI-01	Level Indicator	Level Indicator	Indicates the water level in WT-01	External Leak of Process Medium (Water)	Unlikely	Leak of water for LI-01 leads to a minor release of H2 into the environment.	Normal	H2-01, WS-01	Serious	Medium
				External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (Water)	Unlikely	Rupture of water from LI-01 leads to a major release of H2 into the environment.	Normal	H2-01, WS-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01, WS-01	Catastrophic	High
HV-05	Hand Valve	Hand Valve	Connects WT-01 to drainage system	External Leak Process Medium (Water)	Unlikely	Leak of water from HV-05 which can cause an insufficient water seal in WT-01. This results in a minor H2 release to the environment.	Normal	H2-01, WS-01	Serious	Medium
				External Rupture Process Medium (Water)	Unlikely	Rupture of water from HV-05 which can cause an insufficient water seal in WT-01. This results in a steam/ H2 release to the environment.	Normal	H2-01, WS-01	Catastrophic	High
HV-06	Hand Valve	Hand Valve	Connects WT-01 to drainage system	External Leak Process Medium (Water)	Unlikely	Leak of water from HV-06 which can cause an insufficient water seal in WT-01. This results in a minor H2 release to the environment.	Normal	H2-01, WS-01	Serious	Medium
				External Rupture Process Medium (Water)	Unlikely	Rupture of water from HV-05 which can cause an insufficient water seal in WT-01. This results in a steam/ H2 release to the environment.	Normal	H2-01, WS-01	Catastrophic	High

Functional Group 2: High Temperature Electrolysis Stack

Component ID	Component	Component Description	Component Function	Failure Mode	Likelihood of Occurrence (L)	Consequences of Failure Mode	Operation State	Current Controls and Safeguards	Severity (S)	Risk (R = L x S)
ES-01	**High Temperature Electrolysis Stack**	**High Temperature Electrolysis Stack**	**High Temperature Electrolysis Stack**	**Plugging - at inlet**	**Unlikely**	ES-01 experiences steam starvation which can lead to irreversible degradation of the membrane, mechanical damage of the membrane or oxidation of the cathode. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05**	**Catastrophic**	**High**
					Unlikely	ES-01 experiences steam starvation which can lead to mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, O2-01***	**Catastrophic**	**High**
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-04**	**Catastrophic**	**High**
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, O2-01***	**Catastrophic**	**High**
				Plugging - at outlet	**Unlikely**	ES-01 experiences a buildup of pressure due to the accumulation of H2 and steam which can lead to mechanical damage of the membrane or oxidation of the cathode. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05**	**Catastrophic**	**High**
					Unlikely	ES-01 experiences a buildup of pressure due to the accumulation of H2 and steam which can lead to mechanical damage of the membrane or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, O2-01***	**Catastrophic**	**High**
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-04**	**Catastrophic**	**High**
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, O2-01***	**Catastrophic**	**High**
				Inherent Membrane Flaws	**Unlikely**	Due to inherent membrane flaws during the manufacturing and assembly process the gas tighness of the stack can be subpar. This can lead to a higher rate of degradation of the stack. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-05, O2-01***	**Catastrophic**	**High**
					Unlikely	Due to inherent membrane flaws during the manufacturing and assembly process, this can result in crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, O2-01***	**Catastrophic**	**High**
				Internal rupture process medium (oxygen)	**Remote**	During startup or shutdown only, this can lead to the occurrence of crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**N/A**	**Catastrophic**	**Medium**
				Internal leak hydrogen	**Remote**	Internal leak of hydrogen can lead to oxidation of the cathode, Ni depleton or damage to the membrane of ES-01. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**N/A**	**Catastrophic**	**Medium**
					Remote	During startup or shutdown only, an internal leak of hydrogen can lead to the occurrence of crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**N/A**	**Catastrophic**	**Medium**
				Internal rupture hydrogen	**Remote**	This can lead to oxidation of the cathode, Ni depleton or damage to the membrane of ES-01. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**N/A**	**Catastrophic**	**Medium**
					Remote	During startup or shutdown only, an interal rupture of hydrogen can lead to the occurrence of crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**N/A**	**Catastrophic**	**Medium**
				External leak hydrogen	**Unlikely**	Minor release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				External rupture hydrogen	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
DC-01	**DC Power Supply**	**DC Power Supply**	**Supplies DC voltage to ES-01**	**Abnromal Output - High**	**Unlikely**	The power supply provides a high output which can cause thermal damage to the membrane of ES-01. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-05, TT-06**	**Catastrophic**	**High**
					Unlikely	During startup or shutdown, the power supply provides a high output which can cause thermal damage to the membrane of ES-01. This can cause gaseous crossover to occur. A flammable mixture of oxygen and hydrogen can accumulate in V-01 or be vented directly into the furnace.	**Outside of Normal**	**TT-05, TT-06**	**Catastrophic**	**High**
Furnace	**Furnace**	**Furnace**	**Maintains temperature of 800C for ES-01**	**Insufficent Heat Transfer - above optimal**	**Unlikely**	The furnace heats ES-01 to a temperature above 800C. This can cause thermal damage to the membrane of ES-01. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-05, TT-06**	**Catastrophic**	**High**

TT-05	**Temperature Sensor**	**Temperature Sensor**	**Monitors and transmits temperature of the Furnace**	**External Rupture of Process Medium (H2)**	**Unlikely**	Potential for a minor release of H2 into the environment.	**Normal**	**H2-01**	**Serious**	**Medium**
TT-06	**Temperature Sensor**	**Temperature Sensor**	**Monitors and transmits temperature of ES-01**	**External Rupture of Process Medium (H2)**	**Unlikely**	Potential for a minor release of H2 into the environment.	**Normal**	**H2-01**	**Serious**	**Medium**

Functional Group 3: Oxygen Processing and Production

Component ID	Component	Component Description	Component Function	Failure Mode	Likelihood of Occurrence (L)	Consequences of Failure Mode	Operation State	Current Controls and Safeguards	Severity (S)	Risk (R = L x S)
						Air Processing				
CO-03	Air Compressor	Air Compressor	Provides compressed air to sweep oxygen from the anode of ES-01	External Leakage Process Medium (Air)	Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	Medium
					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	Medium
				External Rupture Process Medium (Air)	Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	High
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	High
				Erratic Output - High	Remote	Excess air has the potential to expose the anode electrode to boron, sulfur or silica which can cause irreversible membrane degradation of ES-01 through poisoning. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-14*, TT-13*, TT-06*	Catastrophic	Medium
					Remote	Excess air has the potential to expose the anode electrode to boron, sulfur or silica which can cause membrane degradation of ES-01, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-14*, TT-13*, TT-06*, O2-01*, MF-05	Catastrophic	Medium
				Abnormal Output - High	Remote	Excess air has the potential to expose the anode electrode to boron, sulfur or silica which can cause irreversible membrane degradation of ES-01 through poisoning. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-14*, TT-13*, TT-06*	Catastrophic	Medium
					Remote	Excess air has the potential to expose the anode electrode to boron, sulfur or silica which can cause membrane degradation of ES-01, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-14*, TT-13*, TT-06*, O2-01*, MF-05	Catastrophic	Medium
				Abnormal Output - Low	Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	Medium
					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	Medium
				Spurious Stop	Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	High
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	High
				Fail to Stop	Remote	Continuous exposure to contaminants present in the compressed sweep air such as boron, sulfur and silica can cause damage to the membrane of ES-01. This can cause required downtime to replace the stack.	Normal	MF-04	Catastrophic	Medium
					Remote	Continuous exposure to contaminants present in compressed sweep air such as boron, sulfur and silica can cause damage to the membrane of ES-01, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	Medium
				Fail to operate	Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	High
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	High
PRV-04	Pressure Relief Valve	Pressure Relief Valve	Pressure relief of CO-03	External Leak of Process Medium (Air)	Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	Medium

					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	Medium
				External Rupture of Process Medium (Air)	Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	High
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	High
				Fail Open	Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	High
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	High
				Fail to Close	Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	High
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	High
GV-05	Gate Valve	Gate Valve	Valve that is open during operation to allow the flow of compressed air to ES-01	External Leak of Process Medium (Air)	Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	Medium
					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	Medium
				External Rupture of Process Medium (Air)	Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	High
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	High
BPR-04	Back Pressure Regulator	Back Pressure Regulator	Regulates pressure of Air leaving CO-03 and moving downstream to ES-01.	Abnormal output-high	Remote	Excess air has the potential to expose the anode electrode to boron, sulfur or silica which can cause irreversible membrane degradation of ES-01 through poisoning. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-14*, TT-13*, TT-06*	Catastrophic	Medium
					Remote	Excess air has the potential to expose the anode electrode to boron, sulfur or silica which can cause membrane degradation of ES-01, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	TT-14*, TT-13*, TT-06*, O2-01*, MF-05	Catastrophic	Medium
				Abnormal output-low	Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	Medium
					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	Medium
				Fail Open	Remote	Excess air has the potential to expose the anode electrode to boron, sulfur or silica which can cause irreversible membrane degradation of ES-01 through poisoning. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	TT-14*, TT-13*, TT-06*	Catastrophic	Medium
					Remote	Excess air has the potential to expose the anode electrode to boron, sulfur or silica which can cause membrane degradation of ES-01, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	TT-14*, TT-13*, TT-06*, O2-01*, MF-05	Catastrophic	Medium
				Fail Closed	Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	High

					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, MF-05, O2-01***	**Catastrophic**	**High**
				Fail to Close	**Remote**	Excess air has the potential to expose the anode electrode to boron, sulfur or silica which can cause irreversible membrane degradation of ES-01 through poisoning. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**TT-14*, TT-13*, TT-06***	**Catastrophic**	**Medium**
					Remote	Excess air has the potential to expose the anode electrode to boron, sulfur or silica which can cause membrane degradation of ES-01, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-14*, TT-13*, TT-06*, O2-01*, MF-05**	**Catastrophic**	**Medium**
				Fail to Open	**Unlikely**	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-04**	**Catastrophic**	**High**
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, MF-05, O2-01***	**Catastrophic**	**High**
				External Leak of Process Medium (Air)	**Remote**	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-04**	**Catastrophic**	**Medium**
					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, MF-05, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Air)	**Unlikely**	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-04**	**Catastrophic**	**High**
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, MF-05, O2-01***	**Catastrophic**	**High**
MF-04	**Mass Flow Controller**	**Mass Flow Controller**	**Measures and transmits flow rate of PO-1**	**External Leak of Process Medium (Air)**	**Remote**	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-04**	**Catastrophic**	**Medium**
					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, MF-05, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Air)	**Unlikely**	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-04**	**Catastrophic**	**High**
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, MF-05, O2-01***	**Catastrophic**	**High**
TT-11	**Temperature Sensor**	**Temperature Sensor**	**Measures and transmits temperature of PO-1**	**External Leak of Process Medium (Air)**	**Remote**	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-04**	**Catastrophic**	**Medium**
					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, MF-05, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Air)	**Unlikely**	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-04**	**Catastrophic**	**High**
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, MF-05, O2-01***	**Catastrophic**	**High**
AH-01	**Air Heater**	**Air Heater**	**Heats sweep air to 800C prior to inlet of ES-01**	**Insufficient heat transfer - above optimal**	**Unlikely**	Sweep air at the inlet of ES-01 is at above optimal temperatures. This can lead to irreversible thermal damage of the membrane. This can cause required downtime to replace the stack.	**Normal**	**TT-12, TT-13,TT-14, TT-05,TT-06**	**Catastrophic**	**High**

					Unlikely	Sweep air at the inlet of ES-01 is at above optimal temperatures. This can lead to thermal damage of the membrane which can result in crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	O2-01*, MF-05*, TT-12, TT-13,TT-14, TT-05,TT-06	Catastrophic	High
				External Leak of Process Medium (Air)	Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	Medium
					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	Medium
				External Rupture of Process Medium (Air)	Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	High
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	High
TT-12	Temperature Sensor	Temperature Sensor	Measures and transmits temperature of AH-01	External Leak of Process Medium (Air)	Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	Medium
					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	Medium
				External Rupture of Process Medium (Air)	Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	High
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	High
TT-13	Temperature Sensor	Temperature Sensor	Measures and transmits temperature of PO-1	External Leak of Process Medium (Air)	Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	Medium
					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	Medium
				External Rupture of Process Medium (Air)	Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	High
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	High
GH-02	Guard Heater	Guard Heater	Secondary heating sweep air to 800C prior to inlet of ES-01	Insufficient heat transfer - above optimal	Unlikely	Sweep air at the inlet of ES-01 is at above optimal temperatures. This can lead to irreversible thermal damage of the membrane. This can cause required downtime to replace the stack.	Normal	TT-12, TT-13,TT-14, TT-05,TT-06	Catastrophic	High
					Unlikely	Sweep air at the inlet of ES-01 is at above optimal temperatures. This can lead to thermal damage of the membrane which can result in crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	O2-01*, MF-05*, TT-12, TT-13,TT-14, TT-05,TT-06	Catastrophic	High
				External Leak of Process Medium (Air)	Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	Medium
					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	Outside of Normal	MF-04, MF-05, O2-01*	Catastrophic	Medium
				External Rupture of Process Medium (Air)	Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	Normal	MF-04	Catastrophic	High

					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, MF-05, O2-01***	**Catastrophic**	**High**
TT-14	**Temperature Sensor**	**Temperature Sensor**	**Measures and transmits temperature of PO-1**	**External Leak of Process Medium (Air)**	**Remote**	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-04**	**Catastrophic**	**Medium**
					Remote	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, MF-05, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Process Medium (Air)	**Unlikely**	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination. This can cause irreversible damage to the stack, which requires facility downtime to replace the stack.	**Normal**	**MF-04**	**Catastrophic**	**High**
					Unlikely	Accumulation of oxygen in the anode of ES-01. This buildup of pressure can cause irreversible membrane degradation, including delamination, which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-04, MF-05, O2-01***	**Catastrophic**	**High**

Functional Group 4: Hydrogen Production and Recycle

Component ID	Component	Component Description	Component Function	Failure Mode	Likelihood of Occurrence (L)	Consequences of Failure Mode	Operation State	Current Controls and Safeguards	Severity (S)	Risk (R = L x S)
						H2 PRODUCTION				
CV-02	Check Valve	Check Valve	Prevent the backflow of N2/H2 mixture into PN-1 and V-02	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				Fail Closed	Unlikely	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. This can cause required downtime to replace the stack.	Normal	O2-01, MF-05	Catastrophic	High
					Unlikely	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	O2-01, MF-05	Catastrophic	High
GH-01	Guard Heater	Guard Heater	In line heater for process gas prior to the inlet of ES-01.	Insufficient heat transfer - above optimal	Unlikely	H2 is fed into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause required downtime to replace the stack.	Normal	O2-01, MF-05	Catastrophic	High
					Unlikely	H2 is fed into the stack at above optimal temperature leading to accelerated membrane degradation, which can cause crossover to occur. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	O2-01, MF-05	Catastrophic	High
				External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
AC-01A/B/C	Finned Air Coolers	Finned Air Coolers	Cools produced H2 to 150C	Insufficient heat transfer - below optimal	Unlikely	Insufficient cooling in AC-01A/B/C can cause insufficient drying of H2 in the condensers. This can cause required downtime to replace the stack.	Normal	TT-07A/B/C, TT-08A/B/C/D*, TT-09, TT-10	Catastrophic	High
					Unlikely	Insufficient cooling in AC-01A/B/C can cause insufficient drying of H2 in the condensers. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	TT-07A/B/C, TT-08A/B/C/D*, TT-09, TT-10, O2-01*	Catastrophic	High
				Plugging - at inlet	Unlikely	Blockage of flow from outlet of ES-01 which leads to insufficient gas removal. This could cause a buildup of pressure in the cathode which would lead to a rupture of the membrane. This would result in the release of a H2 and O2 mixture leading to a potential fire in ES-01.	Normal	TT-07A/B/C	Catastrophic	High
				External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
TT-02	Temperature Sensor	Temperature Sensor	Measures and transmits temperature of PH-1 directly after SG-01	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
TT-03	Temperature Sensor	Temperature Sensor	Measures and transmits temperature of PH-1	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
TT-04A	Temperature Sensor	Temperature Sensor	Measures and transmits temperature of PH-1	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
TT-04B	Temperature Sensor	Temperature Sensor	Measures and transmits temperature of PH-3	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
TT-07A/B/C	Temperature Sensor	Temperature Sensor	Measures and transmits temperature of AC-01 A/B/C	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
						H2 Recycle				
TT-09	Temperature Sensor	Temperature Sensor	Measures and transmits temperature of PH-5	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
PT-02	Pressure Sensor	Pressure Sensor	Low pressure sensor, triggers CO-01 to start recycle process	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
CV-05	Check Valve	Check Valve	Prevents the backflow of H2 from the vent	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	High

				External Rupture of Process Medium (H2)	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
CO-01	**H2 Compressor**	**H2 Compressor**	**Compresses H2 for storage**	**Abnormal Output - Low**	**Unlikely**	Build up of H2 in PH-5, this forces hydrogen to back feed into ES-01 which causes inefficient gas removal. This could cause a buildup of pressure in the cathode which would lead to a rupture of the membrane. This would result in the release of H2 and O2 leading to a potential fire in ES-01.	**Normal**	**MF-05, H2-01, CV-05**	**Catastrophic**	**High**
					Remote	Build up of H2 in PH-5, CO-1 is unable to supply V-01 with the correct amount of H2. Over time, this will drain V-01 and cause an insufficient amount of H2 at the inlet of ES-01. This will cause membrane damage of ES-01. This can cause required downtime to replace the stack.	**Normal**	**MF-05**	**Catastrophic**	**Medium**
					Remote	Build up of H2 in PH-5, CO-1 is unable to supply V-01 with the correct amount of H2. Over time, this will drain V-01 and cause an insufficient amount of H2 at the inlet of ES-01. This will cause membrane damage of ES-01. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, O2-01***	**Catastrophic**	**Medium**
				Abnormal Output - High	**Remote**	Excess H2 will accumulate in V-01.This can cause V-01 to experience mechanical stresses and lead to a major leak of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**Medium**
					Unlikely	High output from CO-01 can create a vacuum upstream. This can cause H2 to flow through AC-01A/B/C and Cond A/B/C/D at a faster rate. H2 will not be sufficiently cooled. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause required downtime to replace the stack.	**Normal**	**TT-07A/B/C, TT-08A/B/C/D, TT-09,TT-10, PT-02**	**Catastrophic**	**High**
					Unlikely	High output from CO-01 can create a vacuum upstream. This can cause H2 to flow through AC-01A/B/C and Cond A/B/C/D at a faster rate. H2 will not be sufficiently cooled. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-07A/B/C, TT-08A/B/C/D, TT-09,TT-10, PT-02, O2-01***	**Catastrophic**	**High**
				External Leak of Process Medium (H2)	**Unlikely**	Minor release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				External Rupture of Process Medium (H2)	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				Erratic Output - tends high	**Unlikely**	Excess H2 will accumulate in V-01.This can cause V-01 to experience mechanical stresses and lead to a major leak of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**Medium**
					Remote	High output from CO-01 can create a vacuum upstream. This can cause H2 to flow through AC-01A/B/C and Cond A/B/C/D at a faster rate. H2 will not be sufficiently cooled. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause required downtime to replace the stack.	**Normal**	**TT-07A/B/C, TT-08A/B/C/D, TT-09,TT-10, PT-02**	**Catastrophic**	**High**
					Unlikely	High output from CO-01 can create a vacuum upstream. This can cause H2 to flow through AC-01A/B/C and Cond A/B/C/D at a faster rate. H2 will not be sufficiently cooled. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-07A/B/C, TT-08A/B/C/D, TT-09,TT-10, PT-02, O2-01***	**Catastrophic**	**High**
				Fail to Operate	**Unlikely**	Build up of H2 in PH-5, this forces hydrogen to back feed into ES-01 which causes inefficient gas removal. This could cause a buildup of pressure in the cathode which would lead to a rupture of the membrane. This would result in the release of H2 and O2 leading to a potential fire in ES-01.	**Normal**	**MF-05, H2-01**	**Catastrophic**	**High**
					Unlikely	Build up of PH-5. Complete loss of recycle system. Over time, this would drain the H2 from V-01 and cause a decrease in the percentage, by volume, of H2 at the inlet of ES-01. This will cause membrane damage or oxidation of the cathode. This can cause required downtime to replace the stack.	**Normal**	**MF-05**	**Catastrophic**	**High**
					Unlikely	Build up of PH-5. Complete loss of recycle system. Over time, this would drain the H2 from V-01 and cause a decrease in the percentage, by volume, of H2 at the inlet of ES-01. This will cause membrane damage or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, O2-01***	**Catastrophic**	**High**
				Spurious Stop	**Unlikely**	Build up of H2 in PH-5, this forces hydrogen to back feed into ES-01 which causes inefficient gas removal. This could cause a buildup of pressure in the cathode which would lead to a rupture of the membrane. This would result in the release of H2 and O2 leading to a potential fire in ES-01.	**Normal**	**MF-05, H2-01**	**Catastrophic**	**High**
					Unlikely	Build up of PH-5. Complete loss of recycle system. Over time, this would drain the H2 from V-01 and cause a decrease in the percentage, by volume, of H2 at the inlet of ES-01. This will cause membrane damage or oxidation of the cathode. This can cause required downtime to replace the stack.	**Normal**	**MF-05**	**Catastrophic**	**High**

					Unlikely	Build up of PH-5. Complete loss of recycle system. Over time, this would drain the H2 from V-01 and cause a decrease in the percentage, by volume, of H2 at the inlet of ES-01. This will cause membrane damage or oxidation of the cathode. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, O2-01*	Catastrophic	High
CV-06	**Check Valve**	**Check Valve**	**Prevents the backflow of H2 into CO-01**	**Fail Closed**	**Unlikely**	H2 would build up downstream of the stack and back feed into CO-01. This would cause a buildup of pressure that can lead to a leak or rupture of CO-01.	**Normal**	**PRV-05A/B/C, H2-01**	**Catastrophic**	**High**
				External Leak of Process Medium (H2)	**Unlikely**	Minor release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				External Rupture of Process Medium (H2)	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
PRV-05A/B/C	**Pressure Relief Valve**	**Pressure Relief Valve**	**Pressure relief of CO-01**	**External Leak of Process Medium (H2)**	**Unlikely**	Minor release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				External Rupture of Process Medium (H2)	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				Fail Open	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				Fail Closed	**Unlikely**	Buildup of H2 in CO-01, this would cause a buildup of pressure that can lead to a leak or rupture of CO-01.	**Normal**	**H2-01**	**Catastrophic**	**High**
				Fail to Open	**Unlikely**	Buildup of H2 in CO-01, this would cause a buildup of pressure that can lead to a leak or rupture of CO-01.	**Normal**	**H2-01**	**Catastrophic**	**High**
				Fail to Close	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
HX-01	**Heat Exchanger**	**Heat Exchanger**	**Removes remaining water from H2 gas before the gas enters the storage tank.**	**External Leak of Process Medium (H2)**	**Unlikely**	Minor release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				External Rupture of Process Medium (H2)	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
TT-10	**Temperature Sensor**	**Temperature Sensor**	**Measures and transmits temperature of PH-6 after HX-01**	**External Leak of Process Medium (H2)**	**Unlikely**	Minor release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				External Rupture of Process Medium (H2)	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
SV-04	**Solenoid Valve**	**Solenoid Valve**	**Normally open, connects the H2 compressors to V-01 storage tank. Open during recycle process, otherwise closed and fails closed.**	**Fail Closed**	**Unlikely**	Accumulation of H2 in PH-7 which can cause back feeding of H2 into CO-01. This results in a potential leak/rupture from CO-01. This is a major release of H2 into the environment	**Normal**	**CV-06, PRV-05A/B/C, H2-01**	**Catastrophic**	**High**
					Unlikely	Accumulation of H2 in PH-7 which can cause back feeding of H2 into HX-01. This results in a potential leak/rupture from HX-01. This is a major release of H2 into the environment	**Normal**	**H2-01,TT-10***	**Catastrophic**	**High**
				Fail to Open	**Unlikely**	Accumulation of H2 in PH-7 which can cause back feeding of H2 into CO-01. This results in a potential leak/rupture from CO-01. This is a major release of H2 into the environment	**Normal**	**CV-06, PRV-05A/B/C, H2-01**	**Catastrophic**	**High**
					Unlikely	Accumulation of H2 in PH-7 which can cause back feeding of H2 into HX-01. This results in a potential leak/rupture from HX-01. This is a major release of H2 into the environment	**Normal**	**H2-01,TT-10***	**Catastrophic**	**High**
				External Leak Process Medium (H2)	**Unlikely**	Minor release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				External Rupture of Process Medium (H2)	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
CV-07	**Check Valve**	**Check Valve**	**Prevents the backflow of H2 into HX-01**	**Fail Closed**	**Remote**	Accumulation of H2 in PH-7, which results in the loss of H2 recycle system. Overtime, this can cause less then 5% H2 at ES-01 inlet, which results in mechanical damage. This can cause required downtime to replace the stack.	**Normal**	**MF-03**	**Catastrophic**	**Medium**
					Remote	Accumulation of H2 in PH-7, which results in the loss of H2 recycle system. Overtime, this can cause less then 5% H2 at ES-01 inlet, which results in mechanical damage. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-03**	**Catastrophic**	**Medium**
					Unlikely	Accumulation of H2 in PH-7 which can cause back feeding of H2 into CO-01. This results in a potential leak/rupture from CO-01. This is a release of H2 into the environment	**Normal**	**CV-06, PRV-05A/B/C, H2-01, TT-10***	**Catastrophic**	**High**
				External Leak of Process Medium (H2)	**Unlikely**	Minor release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				External Rupture of Process Medium (H2)	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
OS-01	**Oxygen Sensor**	**Oxygen Sensor**	**Detects high levels of oxygen in recycled hydrogen flow**	**External Leak of Process Medium (H2)**	**Unlikely**	Minor release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				External Rupture of Process Medium (H2)	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
MF-05	**Mass Flow Controller**	**Mass Flow Controller**	**Measures and transmits flow rate of PH-7**	**External Leak of Process Medium (H2)**	**Unlikely**	Minor release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
				External Rupture of Process Medium (H2)	**Unlikely**	Major release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**
V-01	**H2 Storage Vessel**	**H2 Storage Vessel**	**H2 Storage Vessel**	**External Leak of Process Medium (H2)**	**Unlikely**	Minor release of H2 into the environment.	**Normal**	**H2-01**	**Catastrophic**	**High**

				External Rupture of Process Medium (H2)	Remote	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	Medium
				Bent/Warped/Damaged	Remote	A leak of water from connection to GV-08 provides a path for minor H2 release.	Normal	H2-02, WS-01	Catastrophic	Medium
					Unlikely	Insufficient sealing with piping connections to V-01 provides a path for a minor H2 release.	Normal	H2-02	Catastrophic	High
PT-03	Pressure Sensor	Pressure Sensor	Measures pressure in V-01	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
PRV-06	Pressure Relief Valve	Pressure Relief Valve	Pressure relief of V-01	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				Fail Open	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
					Remote	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. This can cause required downtime to replace the stack.	Normal	H2-01	Catastrophic	Medium
					Remote	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	H2-01	Catastrophic	Medium
				Fail to Close	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
					Remote	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. This can cause required downtime to replace the stack.	Normal	H2-01	Catastrophic	Medium
					Remote	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	H2-01	Catastrophic	Medium
GV-07	Gate Valve	Gate Valve	Valve that is closed during normal operation	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
BPR-05	Back Pressure Regulator	Back Pressure Regulator	Regulates pressure of H2 leaving V-01	Abnormal output-low	Remote	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. This can cause required downtime to replace the stack.	Normal	H2-01	Catastrophic	Medium
					Remote	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	H2-01	Catastrophic	Medium
				Fail Closed	Unlikely	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. This can cause required downtime to replace the stack.	Normal	H2-01, PT-03, MF-03	Catastrophic	High
					Unlikely	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	H2-01, PT-03	Catastrophic	High
					Remote	Accumulation of H2 in V-01 causes an overpressure which can lead to a leak/rupture of V-01.	Normal	PT-03, PRV-06	Catastrophic	Medium
				External Leak of Process Medium (H2)	Remote	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	Medium
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
GV-08			Used to drain any water from V-01	External Leak of Process Medium (Water)	Remote	A leakage of water from GV-08 can cause an insufficient water seal at the bottom of V-01 which provides a path for a minor H2 release into the environment.	Normal	H2-01, WS-01	Catastrophic	Medium
GV-06	Gate Valve	Gate Valve	Valve that is open during normal operation	External Leak of Process Medium (H2)	Remote	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	Medium
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High

SV-01	Solenoid Valve	Solenoid Valve	Controls flow of hydrogen into ES-01. Normally open during normal operation. Used in alarm conditions to cut off hydrogen supply to ES-01.	Fail Closed	Unlikely	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. This can cause required downtime to replace the stack.	Normal	PT-03, MF-03	Catastrophic	High
					Unlikely	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	PT-03, MF-03	Catastrophic	High
					Remote	Accumulation of H2 in V-01 causes an overpressure which can lead to a leak/rupture of hydrogen from V-01.	Normal	PT-03, PRV-06, MF-03	Catastrophic	Medium
				Fail to Open	Unlikely	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. This can cause required downtime to replace the stack.	Normal	PT-03, MF-03	Catastrophic	High
					Unlikely	ES-01 would not receive H2 on the inlet of the cathode, which would not maintain the proper reducing conditions for the SOEC and can cause accelerated degradation to the cell membrane. During startup or shutdown, this can lead to the occurrence of significant crossover that does not react back into steam. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	PT-03, MF-03	Catastrophic	High
					Remote	Accumulation of H2 in V-01 causes an overpressure which can lead to a leak/rupture of hydrogen from V-01.	Normal	PT-03, PRV-06, MF-03	Catastrophic	Medium
				External Leak Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High
MF-03	Mass Flow Controller	Mass Flow Controller	Measures and transmits flow rate of PH-8	External Leak of Process Medium (H2)	Unlikely	Minor release of H2 into the environment.	Normal	H2-01	Catastrophic	High
				External Rupture of Process Medium (H2)	Unlikely	Major release of H2 into the environment.	Normal	H2-01	Catastrophic	High

Functional Group 5: Nitrogen Supply

Component ID	Component	Component Description	Component Function	Failure Mode	Likelihood of Occurrence (L)	Consequences of Failure Mode	Operation State	Current Controls and Safeguards	Severity (S)	Risk (R = L x S)
						N2 in uses during start up and shutdown ONLY				
V-02	Nitrogen Vessel	Nitrogen Vessel	Stores nitrogen	External Leak of Process Medium (Nitrogen)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
				External Rupture of Process Medium (Nitrogen)	Remote	A rupture of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
BPR-02	Back Pressure Regulator	Back Pressure Regulator	Regulates pressure of N2 leaving V-02 and moving downstream to ES-01.	External Leak of Process Medium (Nitrogen)	Remote	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
				External Rupture of Process Medium (Nitrogen)	Unlikely	A rupture of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
GV-02	Gate Valve	Gate Valve	Closed during normal operation	External Leak of Process Medium (Nitorgen)	Remote	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
				External Rupture of Process Medium (Nitorgen)	Unlikely	A rupture of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
PRV-01	Pressure Relief Valve	Pressure Relief Valve	Pressure relief of PN-1	External Leak of Process Medium (N2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
				External Rupture of Process Medium (N2)	Unlikely	A rupture of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
				Fail Open	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
				Fail to Close	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
MF-02	Mass Flow Controller	Mass Flow Controller	Measures and transmits flow rate of PN-1	External Leak of Process Medium (Nitorgen)	Remote	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
				External Rupture of Process Medium (Nitorgen)	Unlikely	A rupture of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
CV-01	Check Valve	Check Valve	Prevents backflow of gasses into PN-1	External Leak of Process Medium (N2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
				External Rupture of Process Medium (N2)	Unlikely	A rupture of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
PTW-01	3 Way Valve	3 Way Valve	Diverts N2 gas into humidifer	External Leak of Process Medium (N2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
				External Rupture of Process Medium (N2)	Unlikely	A rupture of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
HV-12	Hand Valve	Hand Valve	Vaporized N2 gas exits HU-01	External Leak of Process Medium (N2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High
				External Rupture of Process Medium (N2)	Unlikely	A rupture of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Normal	AT-01	Catastrophic	High

Functional Group 6: Chilled Water Supply

Component ID	Component	Component Description	Component Function	Failure Mode	Likelihood of Occurrence (L)	Consequences of Failure Mode	Operation State	Current Controls and Safeguards	Severity (S)	Risk (R = L x S)
TT-15	**Temperature Sensor**	**Temperature Sensor**	**Measures and transmits temperature of PCW-1**	**External Leak of Utility Medium (Chilled Water)**	**Remote**	Water leakage has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Utility Medium (Chilled Water)	**Unlikely**	Loss of water has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**High**
GV-09	**Gate Valve**	**Gate Valve**	**Chilled water feedback from HX-01. Normally open during operation**	**Bent/warped/damaged**	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-09. This leads to insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires the stack to be replaced. This can cause required downtime to replace the stack.	**Normal**	**TT-10, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-09. This leads to insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-10, WS-01, O2-01***	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-09. This leads to insufficient drying of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires the stack to be replaced. This can cause required downtime to replace the stack.	**Normal**	**TT-10, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-09. This can cause insufficent drying of the produced H2 gas due to the loss of water in the recirculating system. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-10, WS-01, O2-01***	**Catastrophic**	**High**
				Contamination	**Unlikely**	Debris from degradation of the inside of the component can travel through the chilled water functional group and damage the condensers or heat exchnager. This leads to insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires the stack to be replaced. This can cause required downtime to replace the stack.	**Normal**	**TT-10, WS-01**	**Catastrophic**	**High**
					Unlikely	Debris from degradation of the inside of the component can travel through the chilled water functional group and damage the condensers or heat exchnager. This leads to an insufficient cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-10, WS-01, O2-01***	**Catastrophic**	**High**

					Unlikely	Debris from degradation of the inside of the component can travel through the chilled water functional group and damage the condensers or heat exchnager. This leads to an insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires the stack to be replaced. This can cause required downtime to replace the stack.	**Normal**	**TT-10, WS-01**	**Catastrophic**	**High**
					Unlikely	Debris from degradation of the inside of the component can travel through the chilled water functional group and damage the condensers or heat exchnager. This leads to an insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-10, WS-01, O2-01***	**Catastrophic**	**High**
				Full Freezing	**Remote**	Water stagnation in HX-01 results in insufficent secondary drying of H_2. Wet H_2 is fed back into the stack leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	**Normal**	**TT-10, WS-01**	**Catastrophic**	**High**
					Remote	Water stagnation in HX-01 results in insufficent secondary drying of H_2. Wet H_2 is fed back into the stack leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-10, WS-01, O2-01***	**Catastrophic**	**High**
				Partial Freezing	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-09. This leads to insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires the stack to be replaced. This can cause required downtime to replace the stack.	**Normal**	**TT-10, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-09.This leads to an insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-10, WS-01, O2-01***	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-09. This leads to an insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires the stack to be replaced. This can cause required downtime to replace the stack.	**Normal**	**TT-10, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-09.This leads to an insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-10, WS-01, O2-01***	**Catastrophic**	**High**
				Full Plugging	**Remote**	Water stagnation in HX-01 results in insufficent secondary drying of H_2. Wet H_2 is fed back into the stack leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	**Normal**	**TT-10, WS-01**	**Catastrophic**	**High**
					Remote	Water stagnation in HX-01 results in insufficent secondary drying of H_2. Wet H_2 is fed back into the stack leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-10, WS-01, O2-01***	**Catastrophic**	**High**
				Partial Plugging	**Unlikely**	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-09. This leads to insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires the stack to be replaced. This can cause required downtime to replace the stack.	**Normal**	**TT-10, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-09.This leads to an insufficient cooling of the produced H_2 gas. H_2 is fed back into the stack at above optimal temperature leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-10, WS-01, O2-01***	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-09. This leads to an insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack at leading to accelerated membrane degradation. This can cause irreversible damage to the stack, which requires the stack to be replaced. This can cause required downtime to replace the stack.	**Normal**	**TT-10, WS-01**	**Catastrophic**	**High**
					Unlikely	Obstruction to water flow can cause turbulent conditions which lead to the dislodging/fracture around GV-09.This leads to an insufficient drying of the produced H_2 gas. Wet H_2 is fed back into the stack leading to accelerated membrane degradation which can cause crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O_2/H_2 mixture can accumulate in V-01.	**Outside of Normal**	**TT-10, WS-01, O2-01***	**Catastrophic**	**High**

				External Leak of Utility Medium (Chilled Water)	Remote	Water leakage has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	Medium
				External Rupture of Utility Medium (Chilled Water)	Unlikely	Loss of water has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
TT-16	Temperature Sensor	Temperature Sensor	Measures and transmits temperature of PCW-7	External Leak of Utility Medium (Chilled Water)	Remote	Water leakage has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	Medium
					Remote	Water leakage has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	Medium
				External Rupture of Utility Medium (Chilled Water)	Unlikely	Loss of water has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	High
					Unlikely	Loss of water has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	Outside of Normal	MF-05, WS-01, O2-01*	Catastrophic	High
GV-04	Gate Valve	Gate Valve	Connects chiller to drain. Normally closed during operation	External Leak of Utility Medium (Chilled Water)	Remote	Water leakage has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	Normal	MF-05, WS-01	Catastrophic	Medium

					Remote	Water leakage has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**Medium**
					Remote	Water leakage has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**Medium**
				External Rupture of Utility Medium (Chilled Water)	**Unlikely**	Loss of water has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficent cooling of the produced H2 gas. H2 is fed back into the stack at above optimal temperature leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation. This can cause required downtime to replace the stack.	**Normal**	**MF-05, WS-01**	**Catastrophic**	**High**
					Unlikely	Loss of water has the potential to cause insufficent drying of the produced H2 gas. Wet H2 is fed back into the stack leading to accelerrated membrane degradation which can cause the accelerated crossover. During startup or shutdown, this can lead to the occurrence of significant crossover. The O2/H2 mixture can accumulate in V-01.	**Outside of Normal**	**MF-05, WS-01, O2-01***	**Catastrophic**	**High**

Functional Group 7: Safe Gas Supply

Component ID	Component	Component Description	Component Function	Failure Mode	Likelihood of Occurrence (L)	Consequences of Failure Mode	Operation State	Current Controls and Safeguards	Severity (S)	Risk (R = L x S)
N2/H2 Safe Gas used during alarm cond. and standby										
V-03	Safe Gas Storage Vessel	Safe Gas Storage Vessel		External Leak of Process Medium (N2/H2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (N2/H2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
BPR-03	Back Pressure Regulator	Back Pressure Regulator	Regulates pressure of N2/H2 leaving V-03 and moving downstream to ES-01.	External Leak of Process Medium (N2/H2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (N2/H2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
GV-03	Gate Valve	Gate Valve		External Leak of Process Medium (N2/H2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (N2/H2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
PRV-02	Pressure Relief Valve	Pressure Relief Valve		External Leak of Process Medium (H2/N2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (H2/N2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
				Fail Open	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
				Fail to Close	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
SV-02				External Leak Process Medium (Safe Gas)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (Safe Gas)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
CV-03				External Leak of Process Medium (N2/H2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium
				External Rupture of Process Medium (N2/H2)	Unlikely	A leak of N2 could displace the air in the room, which could lead to asphyxiation of facility personal.	Outside of Normal	AT-01	Catastrophic	High
					Unlikely	Minor release of H2 into the environment.	Outside of Normal	H2-01	Serious	Medium

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