ABSTRACT

Title of Thesis:	DEVELOPMENT OF A RELIABILITY DATA COLLECTION FRAMEWORK FOR HYDROGEN FUELING STATION QRA
	Madison West, Master of Science, 2021
Thesis directed by:	Dr. Katrina Groth, Department of Mechanical Engineering

The wider adoption of hydrogen in multiple sectors of the economy requires that safety and risk issues be rigorously investigated. Quantitative Risk Assessment (QRA) is an important tool for enabling safe deployment of hydrogen fueling stations and is increasingly embedded in the permitting process. However, QRA needs reliability data, and currently the available hydrogen safety databases are not in a format conducive for use in QRA. A review of the International Journal of Hydrogen Energy articles on hydrogen fueling station QRA found that lack of hydrogen reliability data is the most common knowledge gap in this field. This study explores what QRA and reliability data currently look like in the context of hydrogen systems. It then presents a new reliability data collection framework for hydrogen systems that overcomes gaps in existing hydrogen safety databases. Current hydrogen safety data collection tools, H2Tools, HIAD, NREL CDPs, and CHS are analyzed and compared for applicability to QRA. Lessons learned from these data collection tools are extracted and combined with best practices from

reliability engineering to create an improved database framework for hydrogen reliability data. This framework aims to standardize the hydrogen fueling stations component hierarchy, failure mode taxonomy, and outline high level elements necessary for adequate reliability data collection suitable for use in QRA. This research establishes the groundwork for a collaborative hydrogen reliability database and the future development of data driven hydrogen safety tools.

DEVELOPMENT OF A RELIABILITY DATA COLLECTION FRAMEWORK FOR HYDROGEN FUELING STATION QRA

by

Madison West

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Chapter 1. Introduction

1.1. Context & Motivation

Due to hydrogen’s enormous potential as a clean energy source, fuel cell electric vehicles have been developed and brought to market. These vehicles run on hydrogen and have no emissions other than water vapor and air. A challenge for the hydrogen industry is developing the infrastructure needed to enable broader adoption of hydrogen vehicles. Hydrogen fueling stations need to be constructed in urban areas in order to support the growth of hydrogen fueled transportation. One of the challenges associated with the development of hydrogen fueling stations is ensuring their safe operation. Safety challenges arise from hydrogen’s properties including wide flammability limit, low minimum ignition energy, high laminar burning velocity, and leakiness [1]–[3]. These properties mean that hydrogen is both prone to be released, and when released into air at high pressure, has the potential to spontaneously ignite, due to the transient shock process associated with rapid failures at high pressure [4].

Hydrogen fueling stations must comply with requirements from safety codes and standards (SCS) in order to be permitted. SCS must be updated in order to expand the deployment of new hydrogen fueling infrastructure especially in urban areas with limited space. One aspect of hydrogen fueling station codes are safety distances, which are minimum distances required between a hazard and a specified target such as another hazard or a property line. Incorporating Quantitative Risk Assessment (QRA) into SCS allows safety distances to be determined using a risk-informed approach. Current SCS for hydrogen like NFPA 2 and ISO 19880-1 use QRA to determine safety distance, however, the reliability data used in these QRA is not hydrogen system specific [5]–[7]. Hydrogen QRA currently relies on generic component failure data from chemical processing, compressed gas, nuclear power, and offshore petroleum industries [8]. Published hydrogen QRA including those by Ade et al. (2020) and Honsellar et al. (2018) use this generic data and cite the need for hydrogen specific reliability data to improve QRA [9], [10]. Due to the lack of hydrogen specific reliability data, it is unclear how well the generic data can accurately predict failure rates for hydrogen fueling infrastructure. During the 2016 HySafe research priorities workshop, tools and resources for QRA was voted the number one hydrogen research priority by experts in the field. One of the resources identified was "hydrogen-specific data for updating probability models" [7]. Creating hydrogen QRA with generic data was a necessary first step in order to develop the first hydrogen fueling codes and standards [8], [11]–[15]. Field data must now be used to generate hydrogen specific reliability data for QRA.

The availability of reliability data for hydrogen fueling infrastructure will allow SCS to create requirements that are science-based and defensible. It will also allow for the improvement in quality and use of performance-based design. This is a major step because it gives stations design freedom to meet their specific needs instead of using a one size fits all approach to safety. Performance-based design using QRA accounts for mitigation measures that cannot be fully considered with prescriptive approaches.

This thesis seeks to address the lack of hydrogen-system specific reliability data by providing a reliability data collection framework for hydrogen fueling stations. The intention is that this framework will be used to create a data collection tool and database for operating hydrogen fueling stations. The product of this database will be anonymous hydrogen reliability data to support QRA with the ultimate goal of making the deployment of hydrogen fueling stations safer and more widely available.

1.2. Objective & Approach

The objective of this research is to enable the deployment of hydrogen fuel and infrastructure by providing new reliability data for use in QRA and safety codes and standards development. This will be achieved by first developing a framework to collect reliability data for hydrogen fueling stations to support QRA. This includes examining current hydrogen safety data collection efforts, QRAs, and industry best practices and applying these lessons learned to hydrogen fueling stations.

To achieve this there are three main tasks:

T1. Review current hydrogen reliability data.

T2. Develop requirements for a hydrogen fueling station reliability data collection framework.

T3. Develop a reliability data collection framework for hydrogen fueling stations.

These three tasks contribute to the development of two subtasks that are described as follows and presented in Figure 1.

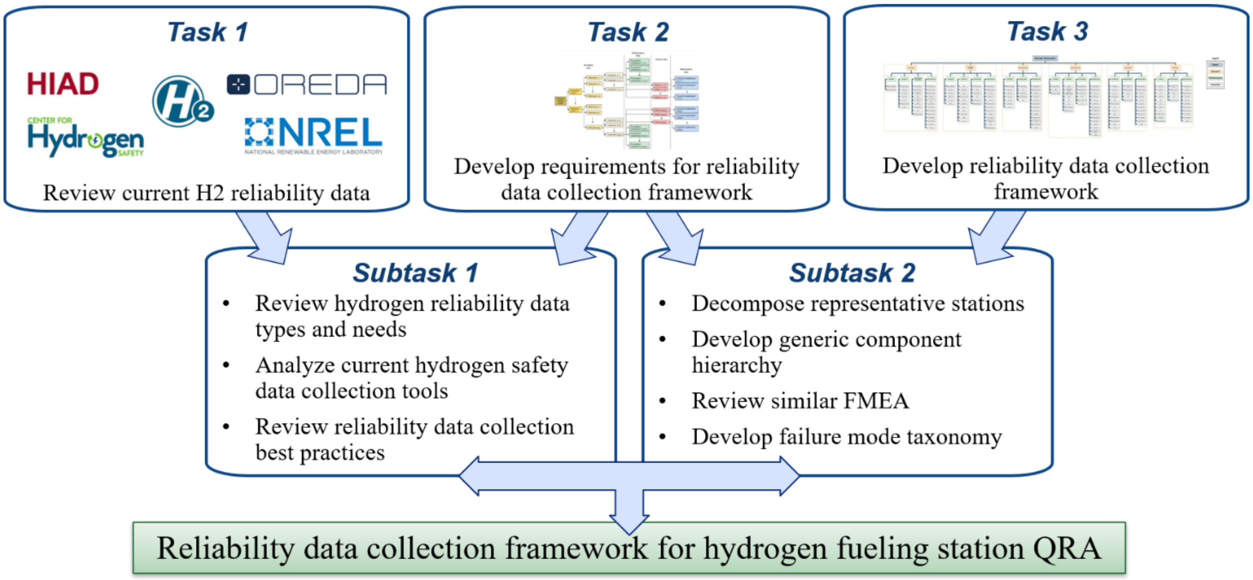


Figure 1 Thesis Task and Subtask Framework

1.2.1. Task 1 Approach: Review and analyze current hydrogen system reliability data

Task 1 began with the review of hydrogen QRA data types and their current availability. In this step, the scope of this thesis is limited to system and frequency data collection. A thorough literature review is used to find four hydrogen safety data collection tools: H2Tools, Hydrogen Incidents and Accidents Database (HIAD), National Renewable Energy Laboratory's (NREL) Composite Data Products (CDPs), and the Center for Hydrogen Safety's (CHS) failure rate data submission form. These data collection tools are analyzed for their completeness, quality, and usability in QRA and lessons learned were determined. Data collection tools and databases from other industries are reviewed to determine reliability data industry best practices. The Offshore and Onshore Reliability Database (OREDA) which collects reliability data for the oil and gas industry is determined to be the most well-developed and applicable to hydrogen of these other reliability data collection tools.

1.2.2. Task 2 Approach: Develop requirements for a hydrogen fueling station reliability data collection framework

Task 2 is the development of requirements for a hydrogen fueling station reliability data collection framework. The results of Task 1's review of current hydrogen safety data collection tools and reliability data collection best practice are used to inform the requirements developed in Task 2. These requirements describe how the data collection tool will operate and what types of data will be collected in order to fill current industry gaps. These requirements will ultimately become part of the hydrogen fueling station reliability data collection framework.

1.2.3. Task 3 Approach: Development of a hydrogen fueling station reliability data collection framework

Task 3 is the development of a hydrogen fueling station reliability data collection framework that will include data collection requirements, a generic component hierarchy, and a failure mode taxonomy. The generic hydrogen fueling station component hierarchy is developed from a representative set of publicly available hydrogen fueling stations, codes and standards, and expert knowledge. A failure mode taxonomy based on hydrogen literature, similar industries taxonomy, and past Failure Modes and Effects Analysis's (FMEA) is developed to correspond with the generic components in the hierarchy. Together, the reliability data collection requirements, generic component hierarchy, and failure mode taxonomy accomplish Task 3, development of a hydrogen fueling station reliability data collection framework.

1.3. Technical Contributions

This work results in three technical contributions which will enable the development of rigorous QRA for hydrogen fueling stations.

1. A list of requirements for hydrogen fueling station data collection are developed. These requirements describe the characteristics and types of data that a hydrogen reliability data collection tool will need in order to collect QRA useable data.
2. A generic component hierarchy for hydrogen fueling stations is created. This hierarchy presents all the components necessary in hydrogen fueling stations and can be used as a tool to inform station design, risk assessment, and the development of a hydrogen reliability data collection tool.
3. A well-defined failure mode taxonomy that corresponds to the generic component hierarchy is characterized. The use of standardized failure modes will improve the

verifiability, reproducibility, and comparability of future hydrogen fueling risk assessment.

Chapter 2. Background & Literature review

Chapter 2 presents three topics that cover the background of this thesis. The first is a description of QRA and how it is applied to hydrogen fueling stations. The second describes the uses of QRA for hydrogen fueling stations, including SCS and station design. The third is a literature review of QRA related to hydrogen infrastructure and presentation of the knowledge gaps therein.

2.1. QRA Fundamentals

2.1.1. Generic QRA process

QRA is a formal and systematic tool to quantify the risk of a process or system. It was developed in the 1970s to address the hazards of the nuclear power industry and has since been adapted to myriad other processes and systems [16], [17]. QRA is particularly useful for determining the risk of dangerous substances such as hydrogen because it considers and quantifies both the realistic hazards and the associated system conditions and failures. The result of a QRA is an estimation of the risk to surrounding people, property, and/or environment which can be used to help decision makers determine an acceptable level of risk. When done properly, QRA results are verifiable, reproducible, and comparable [18].

The fundamental steps in QRA are identifying scenarios that pose a risk, evaluating the consequences of these scenarios, and determining the likelihood of these scenarios. The likelihood and consequence are then multiplied to calculate the risk of each scenario, which are then summed to determine the overall risk of a system. This is illustrated by the following equation for risk where c_i represents a consequence of a hazard scenario, p_i represents the probability of that scenario occurring, and n represents the number of scenarios summed to estimate the total risk.

$$Risk = \sum_{i=1}^{n} p_i \; x \; c_i$$

QRA provides a formal and systematic structure to perform this risk calculation in the context of a specific process or system.

There are many ways to perform QRA that have been developed for different industries but they all follow the same process presented in Figure 2. Modarres' *Risk Analysis in Engineering* describes a high level QRA methodology that can be applied to any process or system [17]. *The Purple Book* is another concise documentation of QRA guidelines designed to determine the risk from the use, handling, transport, and storage of dangerous substances [18].

The assessment begins with scope definition where the purpose of the QRA and boundaries of the system are defined. During scope definition, the system is described in detail including all of the system components, materials, operating conditions, and process flow. Anything that will be considered in the QRA will be documented in this step. An initiating event is the first step in a sequence that may result in a hazard. Initiating events (e.g. loss of containment) that will cause failure to the system are then identified. The two most common qualitative techniques for identifying these events are FMEA and Hazard and Operability Study (HAZOP). Initiating event frequency is determined from reliability data collected on the system or on comparable components. An Event Sequence Diagram (ESD) can be used to document all of the possible scenarios that can occur following the initiating event in order to determine and map the hazard scenarios of interest to the risk assessment. The events in the ESD include all system response and mitigation possibilities. ESDs document the probability of each event that occurs in the sequence. The probability of occurrence of the hazard scenarios are determined by multiplying the probabilities of all of the events leading to that scenario. Hazard scenarios are then modeled to determine their consequences. Different applications will have different consequences of interest which means they will use different models and metrics to evaluate consequence. The risk of each hazard scenario is quantified by multiplying the frequency and consequence of the scenario. Overall system risk is the sum of each hazard scenario. An uncertainty analysis is performed on the results due to the inherent uncertainty using consequence models and event probabilities. Finally, the risk can be evaluated and used as a tool to inform decision makers. Risk matrices and hazard scenario ranking are common ways to communicate risk to stakeholders.

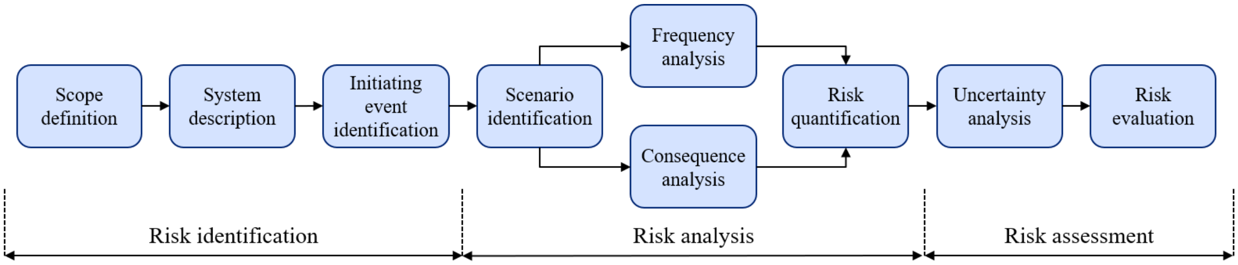


Figure 2 QRA Framework illustrating the main steps in conducting a rigorous QRA

2.1.2. QRA process for hydrogen fueling stations

Hydrogen fueling stations use QRA for safe planning and operation. QRA is used to design stations and to demonstrate hydrogen fueling station compliance with SCS requirements. Several QRA studies on hydrogen fueling stations use a variety of risk modeling tools have been published in literature [10], [15], [19]–[29]. A free open source tool called Hydrogen Risk Assessment Models (HyRAM) has been developed by Sandia National Laboratories specifically for QRA and consequence modeling of hydrogen infrastructure and transportation [14], [30], [31]. The framework for HyRAM QRA is described in by the HyRAM 1.0 Technical reference manual and shown in Figure 3 [31].

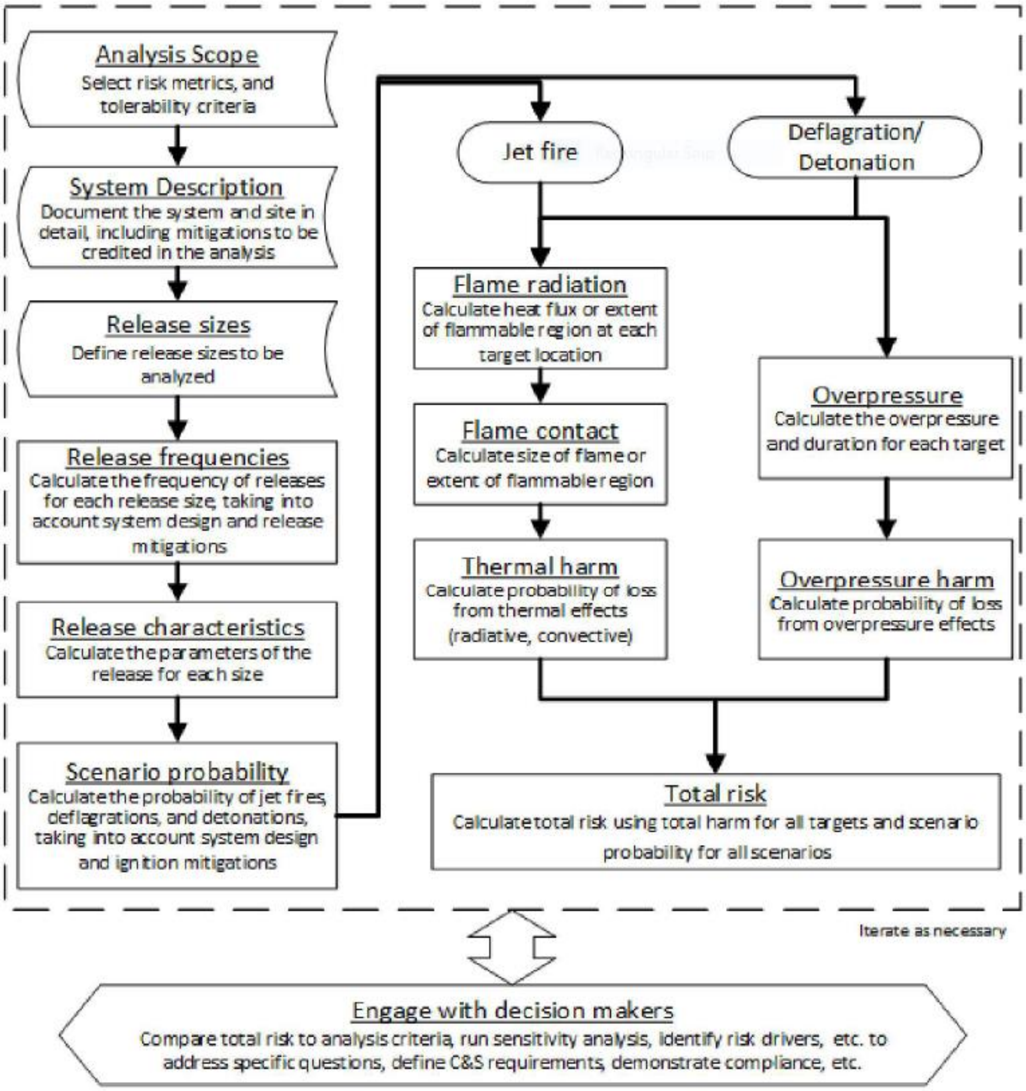


Figure 3 HyRAM QRA Framework from [31].

The first step in the HyRAM framework is defining the purpose of the QRA which includes defining the risk metric and the threshold for tolerable risk. The system is then described including the process, the components, and the risk mitigation measures. Hydrogen releases are the initiating event for risk scenarios in hydrogen systems and release size must be defined for QRA. In HyRAM there are five size options relative to pipe diameter: 0.01%, 0.1%, 1%, 10%, 100%. The frequency of each leak size is calculated based on component leak frequency, dispensing release frequency, and system mitigations. The ignition source of the hydrogen release is not considered because hydrogen can spontaneously ignite when it is release at high pressure, and if there is an outside ignition source it is often impossible to find; HyRAM uses look-up tables for ignition probabilities with increasing probability of ignition for increasing leak sizes. An ESD shown in Figure 4 is used to determine the hazard scenarios and the probability of each. The consequences of the various scenarios following a hydrogen release are unignited release, jet fire, gas fire without overpressure, or gas fire with overpressure (explosion). The probability of each scenario is determined based on release, detection, isolation, and ignition probabilities.

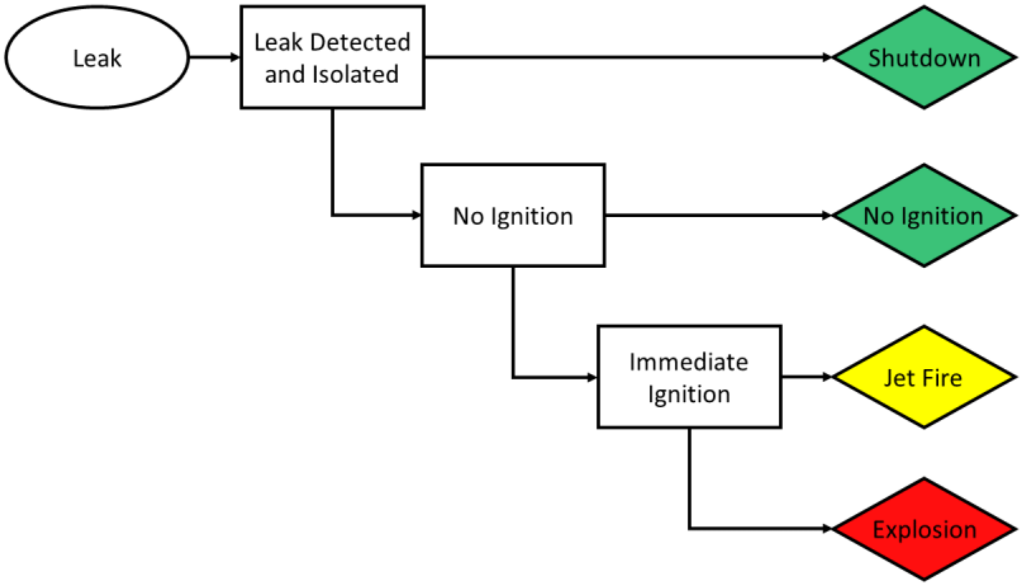


Figure 4 HyRAM Event Sequence Diagram from [14]

The consequences of greatest interest are jet fire and explosion which are modeled using release parameters and exposure location as inputs. The outputs of these models are heat flux for jet fires and overpressure for explosions. Consequence is expressed in Potential Loss of Life (PLL), which is described as the expected fatalities per system year. The mathematical expression for PLL is as follows: where n is one of the safety-significant scenarios, f_n is the frequency of scenario n, and c_n is the expected number of fatalities for scenario n.

$$PLL = \sum_n (f_n \times c_n)$$

PLL can be calculated for target locations throughout the station to create a risk contour, that shows the risk or consequence levels with respect to location as shown in Figure 5 [32]. This is then compared to the tolerable risk level, to inform decision makers.

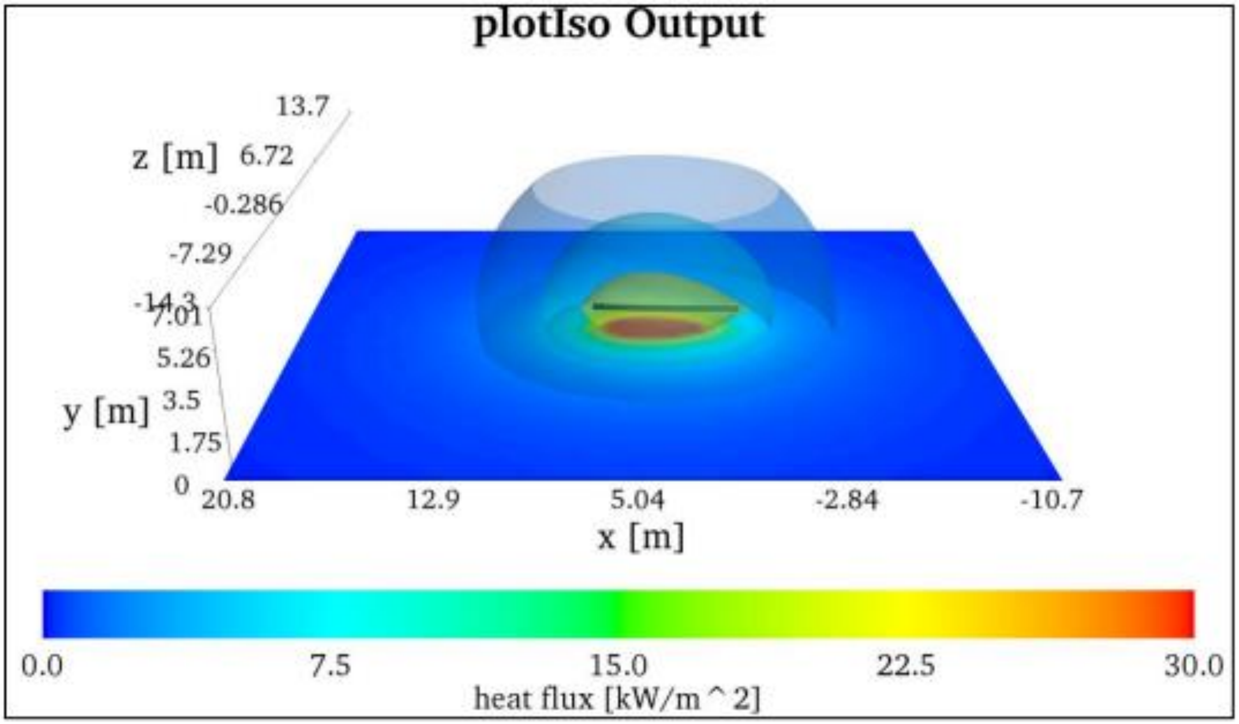


Figure 5 Risk contour from HyRAM [32]

The fundamental steps in QRA are identifying scenarios, evaluating consequence, and determining likelihood, but not all of these aspects of QRA are adequately researched in the context of hydrogen fueling stations. Currently QRAs identify generic failure scenarios but scenario development is limited because there are no sources that list the failure modes for all hydrogen fueling station components. Currently there are no publicly available FMEAs of hydrogen fueling stations at the component level. Rigorous and accurate QRA studies need to be repeatable and comparable to each other. To fill this knowledge gap, a taxonomy of failure modes must be established and hydrogen reliability data accounting for these failure modes must be collected. Scenario likelihood is determined by the component failure rates as well as detection, isolation, and ignition frequencies. Current hydrogen risk assessments all rely on the same generic component leak frequency data developed from offshore petroleum, nuclear, natural gas, and chemical processing industries combined with limited hydrogen specific data from the Compressed Gas Association (CGA) and other partners [8]. This data is a good start and has enabled hydrogen system QRA but there is variability in leakage definition, component classification, operating conditions, and system design. The gas properties of hydrogen are also different than other process fluids. Hydrogen used in transportation applications is extremely pure (>99.999%) meaning there will be no moisture or contaminants in the system. Hydrogen is also very leaky due to its low density and small molecular size. Since there is no hydrogen-system specific data to compare to it is unknown how much these variables affect the suitability of reliability data from other industries to accurately predict hydrogen component failures. The detection and isolation probabilities of hydrogen systems are also not well-known and QRA relies on generic estimations for these frequencies [5]. Developing accurate probability distributions for these system responses is another knowledge gap for the field that will not be directly addressed in this thesis. On the other hand, the consequences associated with hydrogen releases (jet fire and explosion) are well understood and researched in the fire science domain. Validated models utilizing equations of state have been developed to predict hydrogen release behavior and consequence [33]–[38].

Failure mechanisms and root causes are commonly misrepresented as failure modes. To avoid confusion, they are defined here and used as such throughout this thesis. A failure mode is the functional manner in which an item can fail, for example external rupture. A failure mechanism is the physical process that causes damage, for example overpressure. A root cause is the event that initiates the failure mechanism, for example truck collides with tank. In this example, the truck collides with the tank (root cause) initiating overpressure (failure mechanism) which generates external rupture (failure mode).

2.2. QRA applications for hydrogen fueling stations

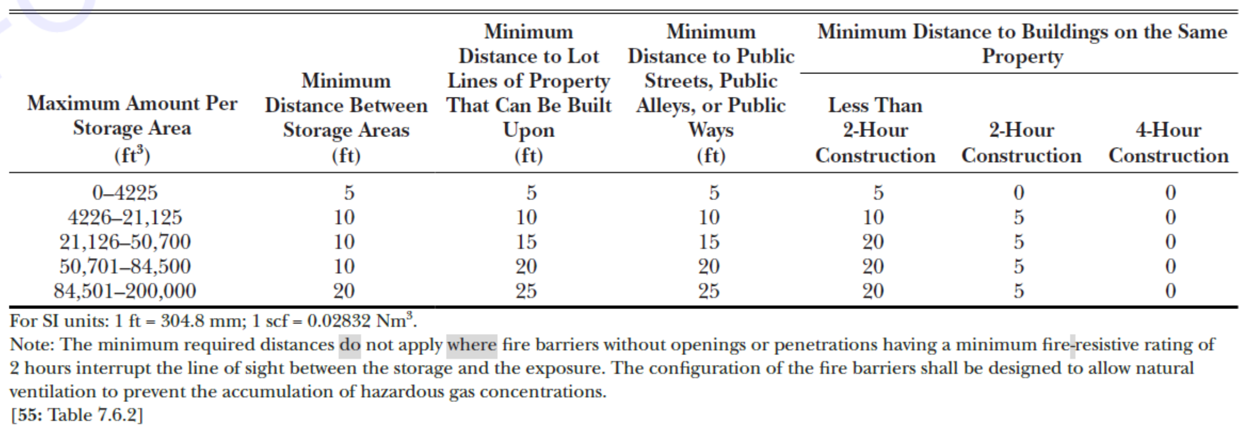
The use of rigorous risk assessment is important to ensure adequate safety at the hydrogen fueling station and to the surrounding area in the event of a failure scenario. To achieve these safety levels, QRA is used in SCS development, compliance demonstration, and facility safety planning [14]. SCS are used to govern the permitting of hydrogen fueling stations around the world. These standards include NFPA2 and NFPA 55 in the US, ISO 19880-1 internationally, CAN/BQN 1784 in Canada, and GB 50177-2005 in China [11]–[13], [39]–[41]. The most technologically advanced of these SCS are NFPA 2 and ISO 19880-1 which use QRA to determine several requirements and allow for a performance-based compliance.

2.2.1. QRA for SCS development

NFPA 2, the Hydrogen Technologies Code, is a US code that defines the minimum requirements for generation, installation, storage, transfer, and use of hydrogen in all applications. ISO 19880-1, the gaseous hydrogen fueling station standard, is an international code that defines the minimum requirements for safe design, installation, operation, and maintenance of hydrogen fueling stations. One safety measure used by these SCS to protect the surrounding people, property, and environment from potentially hazardous scenarios at hydrogen fueling stations is separation distances between station equipment and lot lines. Both NFPA 2 and ISO 19880-1 use the HyRAM QRA methodology to determine acceptable separation distances [11], [12].

The following method explains how HyRAM was used to develop these SCS requirements. Generic hydrogen fueling stations were defined and a risk analysis was performed to determine the risk of predetermined hazard scenarios. Risk thresholds were set for hydrogen lower flammability limit, leak size, and heat flux. Each scenario was evaluated and separation distances were defined to ensure the harm did not exceed the risk guideline.

For NFPA 2, the risk guideline was set at 2×10^{-5} fatalities/yr and a safety factor of 1.5 was applied to the final separation distances. This guideline was chosen to match the average risk of fatality at a gasoline station [42]. This QRA led to the development of several prescriptive separation distance tables based on system characteristics such as pressure and pipe diameter [11]. An example of minimum separation distances between storage areas, to lot lines, to public roads, and to other buildings based on storage area from NFPA 2 is shown in Figure 6. Due to the fact that these separation distances are determined for a range of pressures and pipe diameters, and only consider some mitigations, it is likely that most prescriptive separation distances are overly conservative.



Maximum Amount Per Storage Area (ft^3)	Minimum Distance Between Storage Areas (ft)	Minimum Distance to Lot Lines of Property That Can Be Built Upon (ft)	Minimum Distance to Public Streets, Public Alleys, or Public Ways (ft)	Minimum Distance to Buildings on the Same Property		
				Less Than 2-Hour Construction	2-Hour Construction	4-Hour Construction
0–4225	5	5	5	5	0	0
4226–21,125	10	10	10	10	5	0
21,126–50,700	10	15	15	20	5	0
50,701–84,500	10	20	20	20	5	0
84,501–200,000	20	25	25	20	5	0

For SI units: 1 ft = 304.8 mm; 1 scf = 0.02832 Nm^3.

Note: The minimum required distances do not apply where fire barriers without openings or penetrations having a minimum fire-resistive rating of 2 hours interrupt the line of sight between the storage and the exposure. The configuration of the fire barriers shall be designed to allow natural ventilation to prevent the accumulation of hazardous gas concentrations.

[**55:** Table 7.6.2]

Figure 6 Example of Separation Distances for Non-Bulk GH2 from NFPA 2 Table 7.2.2.3.2 [11]

For ISO 19880-1, five QRA case studies were performed with different risk guidelines to demonstrate the requirements of different regions with varying risk acceptance criteria and assumptions. These five case studies are included in Appendix A as an example for analysts from different regions on how to use QRA to meet ISO 19880-1 requirements. ISO requires users to follow the QRA methodology developed based on HyRAM in conjunction with region specific model inputs.

2.2.2. QRA for compliance demonstration

In order to comply with SCS, hydrogen fueling stations must meet prescriptive guidelines outlined in the code or they must show equivalency with a performance-based approach. Equivalency means designs will meet a safety level that is equal to or better than the requirements described in the code as determined by the Authority Having Jurisdiction. A performance-based design (PBD) follows the steps outlined in Figure 7 [11]. LaFleur, Muna, & Groth (2017) published a methodology for implementing a PBD of an outdoor hydrogen fueling station that meets NFPA 2 requirements [21]. Similar to a QRA, a PBD begins with a definition of the scope of the project which includes the constraints, characteristics, stakeholders, intended use and applicable codes. The goals of the PBD are then established and turned into measurable objectives. The minimum performance criteria for hydrogen hazards from NFPA 2 §5.2 which describe the required minimum level of safety, are listed in Table 1. The minimum design scenarios from NFPA 2 §5.4 which describe the events that must be modeled to demonstrate adequate safety, are listed in Table 2 and a more detailed description of each with examples can be found in NFPA 2 §A.5.4.2. A design brief is prepared with trial designs that are evaluated against the performance criteria and design scenarios. If no designs meet the safety criteria, new designs must be developed or the objectives must be changed. Once the final design is chosen, a design report, specifications, drawings, and operations and maintenance manual is prepared.

While a PBD does not mandate the use of QRA, it is a useful tool to demonstrate compliance.

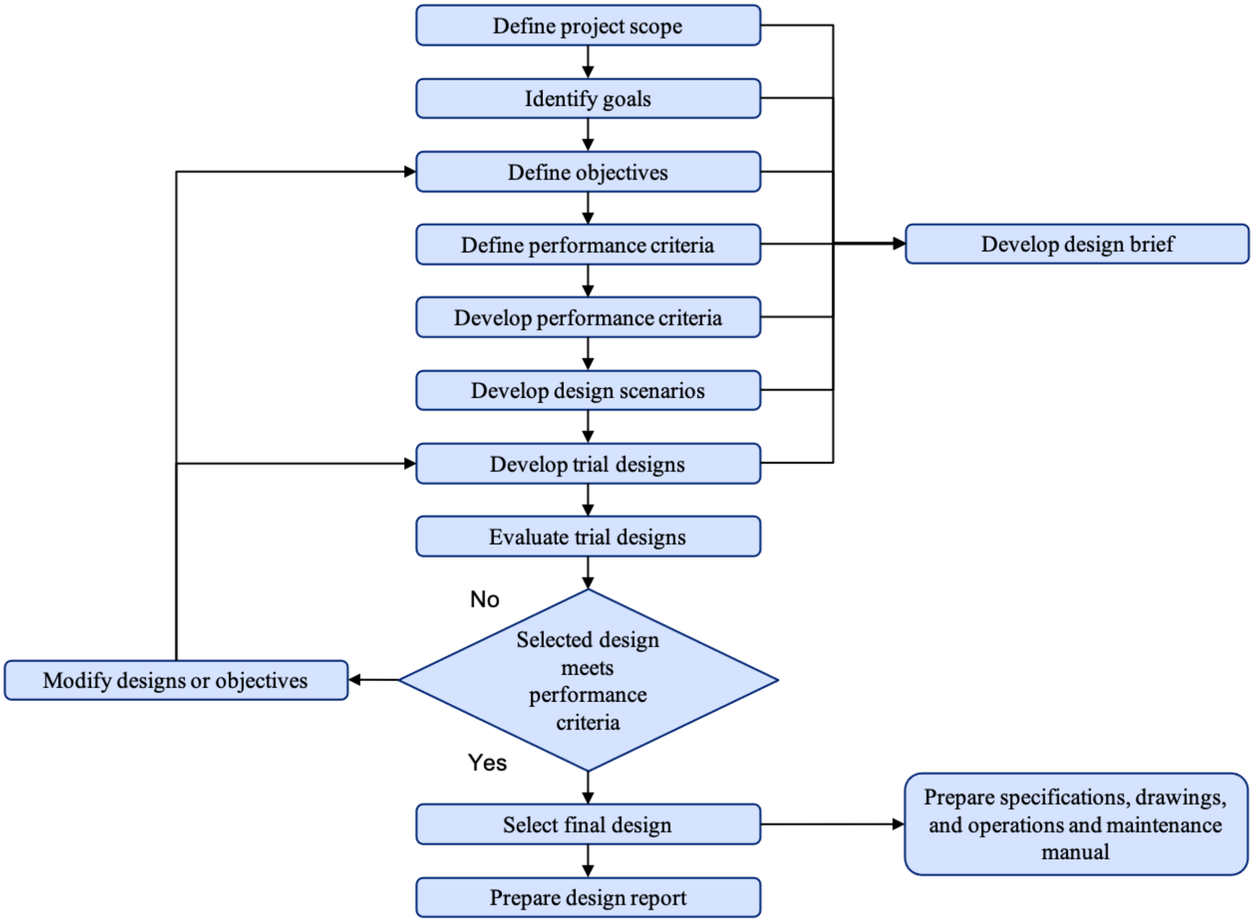


Figure 7 Performance-Based Design Framework adapted from [11]

Table 1 NFPA 2 Performance Criteria (NFPA 2 §5.2) [11]

Performance Criteria	**Description**
Fire Conditions	No occupant who is not intimate with ignition shall be exposed to instantaneous or cumulative untenable conditions.
Explosion Conditions	The facility design shall provide an acceptable level of safety for occupants and for individuals immediately adjacent to the property from the effects of unintentional detonation or deflagration.
Hazardous Materials Exposure	The facility design shall provide an acceptable level of safety for occupants and for individuals immediately adjacent to the property from the effects of an unauthorized release of hazardous materials or the unintentional reaction of hazardous materials to cryogenic hydrogen or precooled hydrogen at the dispenser is established for this analysis.

Property Protection	The facility design shall limit the effects of all required design scenarios from causing an unacceptable level of property damage.
Occupant Protection from Untenable Conditions	Means shall be provided to evacuate, relocate, or defend in place occupants not intimate with ignition for sufficient time so that they are not exposed to instantaneous or cumulative untenable conditions from smoke, heat, or flames.
Emergency Responder Protection	Buildings shall be designed and constructed to reasonably prevent structural failure under fire conditions for sufficient time to enable fire fighters and emergency responders to conduct search and rescue operations.
Occupant Protection from Structural Failure	Buildings shall be designed and constructed to reasonably prevent structural failure under fire conditions for sufficient time to protect the occupants.

Table 2 NFPA 2 Design scenarios (NFPA 2 §5.4) [11]

Design Scenario	**Description**
Fire Scenario	Performance-based building design for life safety affecting the egress system shall be in accordance with this code and the requirements of the adopted building code.
Explosion Scenario 1	Hydrogen pressure vessel burst scenario shall be the prevention or mitigation of a ruptured hydrogen pressure vessel.
Explosion Scenario 2	Hydrogen deflagration shall be the deflagration of a hydrogen-air or hydrogen-oxidant mixture within an enclosure such as a room or within large process equipment containing hydrogen.
Explosion Scenario 3	Hydrogen detonation shall be the detonation of a hydrogen-air or hydrogen-oxidant mixture within an enclosure such as a room or process vessel or within piping containing hydrogen.
Hazardous Material Scenario 1	Unauthorized release of hazardous materials from a single control area.
Hazardous Material Scenario 2	Exposure fire on a location where hazardous materials are stored, used, handled, or dispensed.
Hazardous Material Scenario 3	Application of an external factor to the hazardous material that is likely to result in a fire, explosion, toxic release, or other unsafe condition.
Hazardous Material Scenario 4	Unauthorized discharge with each protection system independently rendered ineffective.

ISO 19880-1 also allows for QRA instead of prescriptive requirements to prove an equivalent or higher level of safety. The framework described in this code and shown in Figure 8 is based on the QRA framework from HyRAM [13]. For a more detailed description of this framework see Section 3.1. Appendix A of ISO 19880-1 includes separation distance calculation examples for different risk acceptance criteria using a generic hydrogen fueling station in HyRAM. ISO does not mandate a specific risk level as NFPA 2 requires risk to be below 2×10^{-5} fatalities/year, however ISO does state that "best practice is to ensure that risk from hydrogen fueling should be equal to or less than the risk posed by similar activities, which could include gasoline fueling, occupational accidents, general accident rates within the population, etc" [12]. Translating this risk statement to frequencies, gasoline fueling risk level is 2×10^{-5} fatalities/year and general accepted accident rates are 1×10^{-6} [42], [43]. The accepted level of risk included in the station design may vary based on location but it must be documented and justified according to the locally accepted standard.

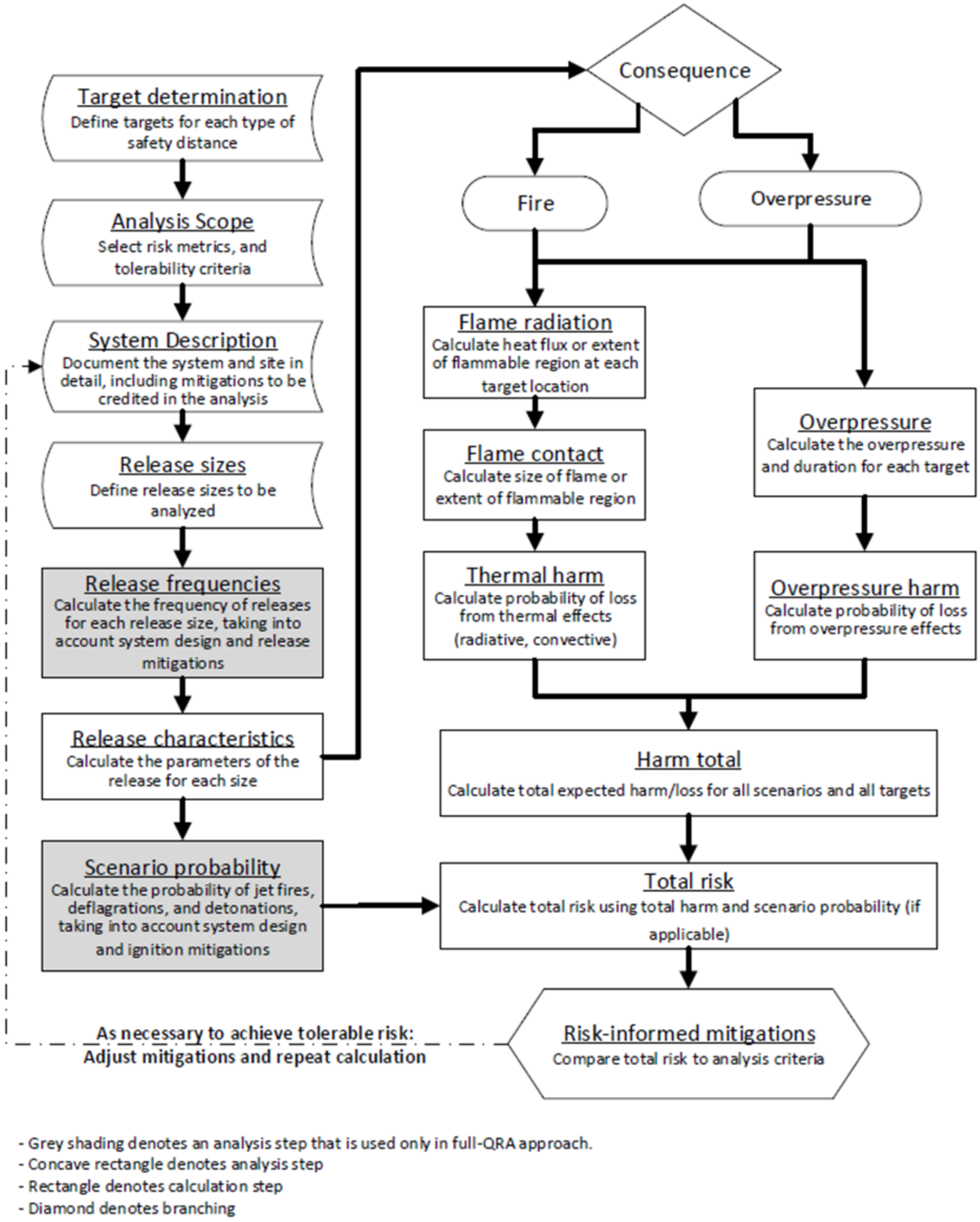


Figure 8 ISO 19880-1 QRA Framework to demonstrate compliance [13]

2.2.3. QRA for facility design and safety planning

QRA can also be used outside of SCS as a tool for facility safety planning. In this context, QRA is used as a tool for designers to see what areas of the hydrogen fueling station have the highest risk level, which failure scenarios pose the greatest threat, and the overall risk level of the hydrogen fueling station. This use case shows where mitigations measures should be focused and allows for a sensitivity analysis to see how different components and mitigation measures affect the total risk level. Due to hydrogen fueling station design variances and different goals for facility safety planning each stations QRA may yield different results. The first QRA from an indoor gaseous hydrogen fueling station was documented by Groth, LaChance, and Harris (2012) to show how this QRA could be performed and share insights into the safety of indoor fueling [15]. Since then, many other hydrogen fueling station QRAs have been published with varying findings. A QRA performed on a Japanese hydrogen fueling station by Suzuki et al. (2021) showed that jet fires are the largest contributor to risk surrounding one station [23]. Zhiyong et al. (2010) used QRA to show that a compressor leak was the greatest risk contributor and could be mitigated by elevating the compressors in a different design [24]. Tsunemi et al (2019) found that the greatest risk for the interior of one hydrogen fueling station was located in the areas directly surrounding the high pressure accumulator and that a 3m barrier combined with 6m of separation distance would reduce the risk to an acceptable level [44]. An urban fueling station QRA by Gye et al. (2019) found that a tube trailer catastrophic rupture caused the station to exceed the acceptable risk level and would require a leak detection system to bring the risk to an acceptable level [27]. QRA for safety planning can be performed using a variety of different methods and with differing outcomes dependent on the studies goals. Regardless of methodology, thorough QRA can be a useful tool for facility safety planners.

2.3. Knowledge gaps in QRA for Hydrogen

A gap study was conducted on articles in the International Journal of Hydrogen Energy (IJHE) in order to better understand the knowledge gaps perceived by authors in the field of hydrogen QRA. A search for articles containing the term QRA within the IJHE database from 2014 to 2021 that are relevant to hydrogen storage, delivery, and operations found 37 articles. Many papers do not identify knowledge gaps, but those that do were recorded and grouped to determine which gaps are identified most frequently. A summary of the three most common knowledge gaps is provided in this section. In order of frequency, these gaps are hydrogen-specific reliability data, consideration of environmental factors, and consideration of human factors. A summary of these findings can be found below in Figure 9.

Figure 9 Summary of key knowledge gaps in hydrogen QRA

2.3.1. Need for hydrogen specific reliability data in QRA

Lack of hydrogen specific reliability data is by far the largest knowledge gap within hydrogen QRA with support from 14 papers. Researchers are looking for a comprehensive and accessible database of hydrogen reliability data to be used in QRA. There are ongoing efforts to create this database but none have successfully captured all of the required hydrogen reliability data and made it publicly available. In 2010 HIAD was created with the intent to collect reliability data for hydrogen QRA but never realized this goal because of lack of reporting [45]. QRA still relies on generic component failure data from other industries due to the lack of publicly hydrogen reliability data.

The extent of this knowledge gap is summarized by Moradi and Groth (2019) in that performing a credible QRA is challenging due to the lack of degradation, failure, and accident data [5]. They propose a comprehensive, accessible database to address this gap. Ade et al. (2020) determine that the lack of hydrogen specific component failure rates is the leading cause of epistemic uncertainty in QRA models. They call for the collection of site specific data, identification failure modes specific to hydrogen fueling stations, and understanding of operation and weather conditions effects on uncertainty [9]. This uncertainty is supported by Honselaar et al. (2018) who find inconsistencies in the component failure frequencies used across QRAs performed on hydrogen fueling stations in the Netherlands [10]. Shirvill et al. (2018) identify the need for hydrogen fueling station data to develop codes and standards and propose that experimental data be collected to fill this gap [46]. The majority of data is focused on gaseous hydrogen, but liquid hydrogen (LH2) reliability data is also needed for component failure rates as described by Groth & Hecht (2017) [14]. Correa-Jullian and Groth (2021) perform a QRA and determine that LH2 reliability data collection is of critical importance to quantify the risks associated with LH2 systems [47]. A report from the Joint Research Center (JRC) identifies the collection of hydrogen specific reliability data as a top hydrogen research priority [48]. QRAs performed by researchers around the world cite lack of hydrogen specific reliability data as a limitation of their work [23], [49]–[51] Huang et al. (2018) and Zarei et al. (2020) use Bayesian Network models to deal with the lack of hydrogen specific data [20], [25]. This is a useful tool for operational stations that can use their own operational reliability data to update their risk models. The authors in the field agree that collection of hydrogen reliability data is one of if not the most pressing issue.

2.3.2. Need for consideration of external factors in QRA

The need for consideration of external factors in hydrogen fueling station QRA is a pressing issue and is noted in six recent papers regarding hydrogen QRA. External factors that can affect hydrogen component failure rates include wind, weather, seismic activity, hurricanes, and security threats among others [48], [50]. It is important to consider the external factors specific to the location of each hydrogen fueling station and their potential effect on failure probabilities. Current hydrogen fueling station specific QRA tools and methodologies do not include guidance on considering external factors in risk assessment. Some experimental QRAs have considered external factors but a standardized approach that can be applied to all QRAs uniformly has not yet been developed [20]. Guidance and criteria for screening and evaluation of external factors is called for by Kotchourko et al. (2014) to address this knowledge gap in a standardized way [48]. Ade et al. (2020) points out that external factors are an area of epistemic uncertainty that researchers do not yet know the magnitude of [9]. QRA researchers including Moradi and Groth (2019), Al-Shanini et al. (2014), Markert et al. (2017), and Skjold et al. (2017) all identify the need for guidance and data on how external factors affect risk at fueling stations and how it can be mitigated [5], [50], [52], [53].

2.3.3. Need for consideration of human factors in QRA

Humans are an integral part of a hydrogen fueling station, playing key roles in the inspection, testing, maintenance, and operation of the system. It is important to think of humans as a part of the system and to account for human impact on accident initiation, propagation, and termination. [54]This knowledge gap is highlighted in five papers within the literature search. An analysis of leak based accidents at hydrogen fueling stations found that human error was responsible for eight out of 43 accidents; about 19% [55]. In order to properly understand and manage risk, human factors must be considered in risk assessment [53]. Human reliability data specific to hydrogen fueling stations should be included in QRA. Moradi and Groth (2019) suggest the use of Bayesian Networks to merge the impact of human errors with system reliability [5]. Ade et al. (2020) suggest that human error probabilities be incorporated with equipment failure rates using human reliability assessment methods [9]. Similar to external factors, some risk assessments have incorporated human factors but there is no standardized guidance yet [20]. There is an argument for considering security threats as a human reliability factor instead of an external factor, but the goal is ultimately for QRA to consider all relevant risk factors [50]. Kotchourko et al. (2014) identify the incorporation of human factors in QRA as one of the top research priorities for hydrogen safety [48].

Chapter 3. Methods, Data, & Results

Chapter 3 presents the methodology, data, and results for the development of a hydrogen fueling station reliability database framework. This process is guided by three tasks pictured in Figure 1. The goal of Task 1 is to review current hydrogen reliability data including the data required for hydrogen QRA, current hydrogen safety data collection efforts, and reliability data collection best practices from other industries. Requirements for a hydrogen reliability data collection framework are then developed in Task 2. Based on those requirements, Task 3 develops a generic component hierarchy and failure mode taxonomy. The generic hydrogen fueling station component hierarchy is synthesized from a representative set of publicly available hydrogen fueling stations, codes and standards, and expert knowledge. A failure mode taxonomy based on hydrogen literature, similar industries, and FMEA like approach is developed to correspond with the generic components in the hierarchy. Together, these form the framework for hydrogen reliability data collection.

3.1. Task 1: Review of current hydrogen reliability data

3.1.1. Method: Review hydrogen reliability data needs, current safety data collection tools, and reliability best practices

To perform Task 1, current hydrogen reliability data types, needs, and collection tools are analyzed to determine what data is available and what data is being collected. All data types relevant to hydrogen QRA are determined and their current availability is reviewed. Literature review and engagement with industry is used to find all hydrogen safety data collection tools: H2Tools, HIAD, NREL’s CDPs, and the CHS Component Failure Rate Data Submission Form.

These data collection tools are analyzed for their quality and usability in QRA. Gaps in data collection and lessons learned are determined.

3.1.2. Data: Data types & needs for hydrogen fueling station QRA

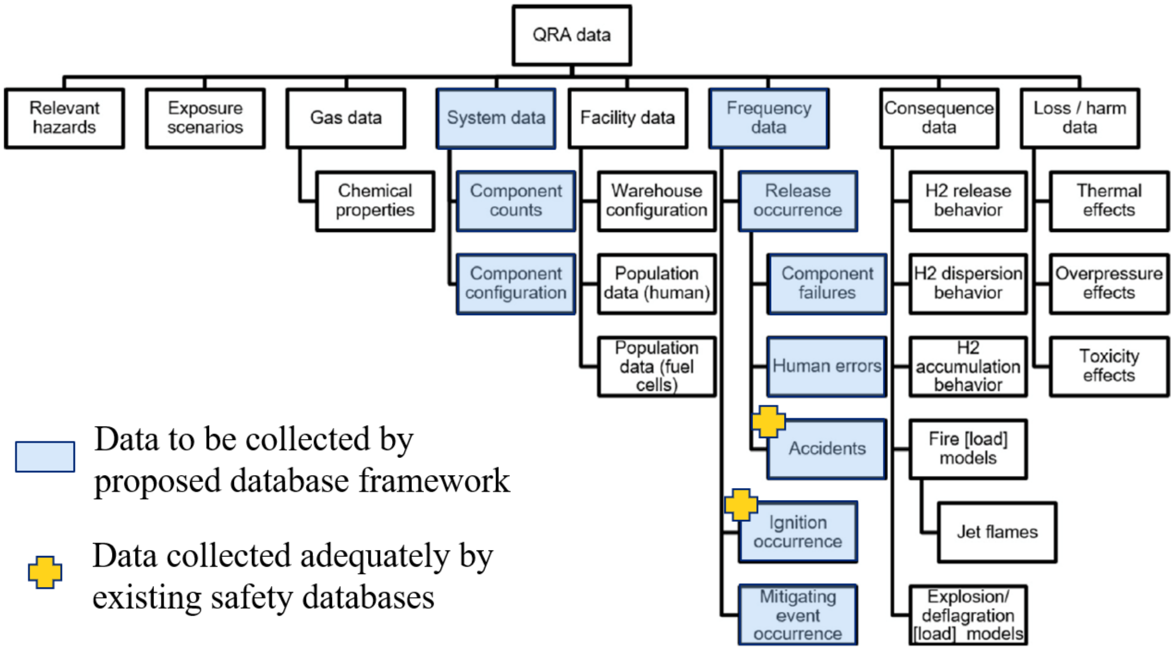


Figure 10 Summary of QRA data used in hydrogen systems including what is covered in this thesis and by other data collection tools, modified from [5]

QRA requires reliability data but this can refer to many different types of data depending on the specifics of the analysis being performed. A review of risk and reliability analysis for hydrogen storage and delivery by Moradi and Groth (2019) summarizing the types of data used in hydrogen QRA is presented in Figure 10 [5]. This covers the data needed to perform all steps of a QRA from hazard and exposure identification to frequency and consequence analysis. The chart has been modified to show what data is covered by this thesis and by current data collection tools. The majority of current hydrogen safety data collection tools only collect what is considered in this chart as accident data and ignition occurrence. These tools may also collect data on component failures, human errors, and mitigation occurrence but the lack of rigor in data collection makes it impossible to develop failure probabilities from this data. As a result, these databases are only being used as safety databases to identify narratives in hydrogen accidents.

The different types of QRA data identified in Figure 10 and the existing gaps therein are discussed below. Current QRA has a good understanding of exposure and hazard scenarios but could use more field data to define failure events and understand potential scenarios that evolve from different types of failures. Gas data is well researched and understood in the physics domain. System data is not currently available for hydrogen fueling stations but is a crucial aspect of well-developed component reliability data. Facility data is available on a per station basis and does not affect component failure rate data so it will not be addressed in the scope of this thesis. Frequency data, which includes component failure is a well-known area of uncertainty in current hydrogen QRA due to the lack of field data. Consequence and loss/harm data is well understood and researched in the fire science domain but the collection of field data related to hazard events at hydrogen fueling stations can be used to refine these models.

Current hydrogen fueling station QRA considers component failure rates for failure modes leading to hydrogen release to determine the frequency of initiating events. These initiating events are modeled in ESDs that lead to hazard scenarios (e.g. jet fire, explosion). The ESD considers system response and physical consequences that may occur following an initiating event. Detection, isolation, and ignition probability data is used to inform these ESD. The data being used by HyRAM for component leak rates was developed using component data from the chemical processing, nuclear power, natural gas, and offshore petroleum industries combined with limited hydrogen data in work by LaChance (2009) [8]. Currently, there is no rigorous scientific basis behind hydrogen detection or isolation probability. HyRAM uses a default constant for probability of detection and isolation of 0.9, which in practice should vary with ventilation, sensor placement, leak location, ability of sensor to operate, and ability of isolation valve to operate [14]. In HyRAM, the ignition probabilities for hydrogen are based on the release rate and are separated into three generic sizes with immediate and delayed ignition probabilities presented in Table 3, based on work from Tchouvelev et al. (2007) [56]. All of these probabilities need to be updated based on actual field data from hydrogen fueling stations.

Table 3 HyRAM ignition probabilities [14]

H_2 Release Rate (kg/s)	P(Immediate Ignition)	P(Delayed Ignition)
<0.125	0.008	0.004
0.125 – 6.25	0.053	0.027
>6.25	0.230	0.120

3.1.3. Data: Current H_2 safety data collection tools

3.1.3.1. H2Tools Lessons Learned

H2Tools Lessons Learned is an anonymous accident database that collects reports on events and near misses related to hydrogen. It was built in 2006 and is maintained by the Pacific Northwest National Laboratory. This database was built as a user friendly, online tool to share lessons learned from hydrogen safety incidents around the world to prevent them from happening in the future. As of October 2021, the database contained 221 reports. These reports come from historic databases, journal articles, other documents, media, and self-reporting [57].

The data collected on events is presented in open-ended narrative fields or a predetermined list of qualitative data with the goal of getting an understanding of the event, cause, severity, consequences, and lessons learned. A complete list of data fields is presented in Table 4. Data fields with predetermined options like equipment are very high level, for example piping and valves are grouped as one equipment type. This is not specific enough to create reliability data that is useable for hydrogen QRA. For open-ended fields, the variety of responses from reporters is so varied that it requires significant user interpretation to make comparisons between multiple events. Also, due to the nature of historic sources and voluntary reporting, most data fields are not mandatory and many incidents have incomplete descriptions. This leads to varying levels of quality in the events that have been reported. All of these characteristics make it hard to create data products from the reports.

Table 4 H2Tools event reporting data entry fields

H2Tools event reporting data entry fields
Severity
Leak
Ignition
Ignition source
Setting
Equipment
Damage/Injuries
Probable cause
Contributing factors
Characteristics
When the incident was discovered
Lessons learned

Despite the difficulty of working with this type of data, H2Tools Lessons Learned creates a presentation of key themes found in the database. These include hydrogen leak detection, ventilation, material compatibility, and burst disk failures among others. These themes are presented as problems with references to specific related events and best practices to mitigate these events in the future.

While the lessons learned from H2Tools are useful for process design and operation, they are not useable as QRA data. A review of published risk assessments using data from H2Tools found that researchers were only able to extract generic cause and effect data. Mirza et al. (2011) uses 32 incident reports related to hydrogen processing from the database to conclude that 43.7% of hydrogen incidents resulted in fires and that technical, operator error, and design error are the majority of primary cause factors [58]. Lam et al. (2019) uses 100 hydrogen logistics incidents from a variety of databases including H2Tools in a network model to analyze the interdependencies of cause and effect. This study finds that inappropriate operation is the most significant cause, leakage is the most significant effect, and that incidents could be reduced by 76% if both inappropriate operation and leakage were controlled [59]. H2Tools Lessons Learned is a safety database that collects qualitative data best-suited for safety culture, planning, procedures, and best practices. While it has been used for high level risk assessment, the lack of quantitative data bars this tool from being used for QRA.

3.1.3.2. HIAD

HIAD is an anonymous platform similar to H2Tools, for hydrogen related event reporting and sharing lessons learned. HIAD was initially developed as part of HySafe in 2004 but is now maintained by the European Commission JRC. The initial goal of this database was to be a lessons learned and risk communication platform as well as a data source for risk assessment. However, in 2016, the database was redesigned and simplified to focus on sharing lessons learned and developing safety awareness because of a lack of data reporting from the private sector [45]. The database currently contains 598 incidents, dating back to 1937, that have been reported from historic databases, journal articles, other documents, media, and self-reporting [60].

After the 2016 update, data entry fields shifted to a completely qualitative combination of narrative fields and predetermined options. Like H2Tools, the goal of incident reporting is to determine the nature of the event, the facility and setting, the consequences, and lessons learned. A complete list of data entry fields is presented in Table 5. HIAD includes a comprehensive and well documented data entry form but many of these fields are missing from reported events. This has created a lack of standardized data reporting. Given that so many entry fields are missing, reliability data cannot be created from these reports.

Table 5 HIAD event reporting data entry fields

Events	**Facility**	**Consequences**	**Event nature**
Description	Application chain	Total number of injured persons	Emergency action
Event classification	Application	Total number of fatalities	Emergency evaluation
Physical consequences	Storage medium	Environmental damage	Release type
Application stage	Storage quantity	Currency	Release concentration
Systems involved	Actual pressure	Property loss (onsite)	Release duration
Region	Design pressure	Property loss (offsite)	release rate
Country	Location type	Post-event summary	Release amount
Date	Location description	Investigation comments	Release pressure
Cause	Operational condition		Hole shape
Cause comments	Pre-event summary		Hole length
Weather			Hole width
Lessons learned			Hole diameter
References			Hole area
			Ignition source
			Ignition delay
			detonation
			Deflagration
			High pressure explosion
			High voltage explosion
			Flame type
			Cloud surface
			Cloud volume
			Flame length
			Flame surface
			Flame volume
			Heat radiation

The lack of consistent data reporting poses a challenge to creating products from this data. The JRC summarized and analyzed the hydrogen events in a report in 2019. This report shows accidents by application, initiating event, geographic location, and compiles individual lessons learned into themes. The themes include inspection and maintenance, personnel, process/plant modifications, and miscellaneous cases. The lessons learned are written in broad terms for example a call for improved maintenance and adhering to maintenance procedures [61]. HIAD data is only be synthesized into narratives and safety advice.

A review of HIAD's use in publications found that the events are used in the same way as the H2Tools database. The paper by Lam et al. (2019) that is described in the H2Tools section also uses events from HIAD to draw conclusions about the interdependence of event cause and effect [59]. A study by Spada et al. (2018) uses data from a number of sources including HIAD to determine the risk of hydrogen compared to other energy sources. Fatality rate and consequence rate are used as the risk indicators to compare these energy sources and the facility and consequence data is gathered from event reporting in databases such as HIAD [62]. Like H2Tools, HIAD is a safety database from which high-level conclusions and general best practices can be derived. While HIAD can support cause and effect analysis, it does not provide the data needed to support QRA.

3.1.3.3. NREL CDPs

NREL collects operation and maintenance data from 44 hydrogen fueling stations operating in the US as of 2020 [63]. This data is aggregated across multiple systems, sites, and teams. The data is processed into an anonymous data product that is published twice a year called a CDP. These CDPs are available to the public and intended to be used as a guide for future research and innovation.

The stations reporting to NREL are under contract to report as part of their permitting so detailed, station specific data is collected at regular intervals and is standardized across all reporting stations. NREL collects data about site summary, fuel logs, fill performance, dispensing, compression, delivery, hydrogen cost, and hydrogen quality in addition to failure and maintenance data. While not currently published, this data could allow for the development of failure rates based on number of demands for hydrogen fueling station components. The failure and maintenance data fields that are collected are presented in Table 6. NREL's data collection does attempt to capture the location of the failure within the system as well as the cause and effect. However, the operating conditions are not collected and most importantly the failure modes are not adequately developed. The data that NREL collects regarding "failure cause" is actually a partially complete mixture of failure modes, mechanisms, and descriptions that are not unique or collectively exhaustive. This data is incorrectly referred to in CDPs as "failure modes" (shown in Figure 11). Appropriately defined failure modes should be developed in addition to failure causes in order to collect QRA useable data. While the quantitative data collected could be used to create some generic component failure frequencies, NREL is only providing a qualitative product, likely due to the contract they have with the stations.

Table 6 NREL CDP event reporting data entry fields

Failure	**Maintenance**
Date	Date
Subsystem	Subsystem
Event description	Component
Lessons learned	Component part number
Severity	Initial failure symptoms
Hydrogen leak	Action
Hydrogen environment	Cause
Component involved	Effect
Component part number	Hydrogen environment
Primary factor	Amount of time dispenser offline
Secondary factors	Event addresses a safety issue
Damages	Description of maintenance
Injuries	

The CDPs describe data regarding deployment, safety, maintenance and reliability, performance, cost, utilization, hydrogen quality, and component energy [63]. These visualizations include breakdown by maintenance cost, time, component, failure mode, amount dispensed, cause, and effect. An example CDP is shown in Figure 11 and describes the "failure modes" for top equipment categories at retail stations. While called failure modes, these are actually a partially defined, non-exhaustive list of failure causes. The maintenance and reliability CDPs summarize the data into bar graphs and pie charts to ensure the anonymity of stations. This presents a visualization of trends over time but it removes the potential for most quantitative data to be determined from the CDPs.

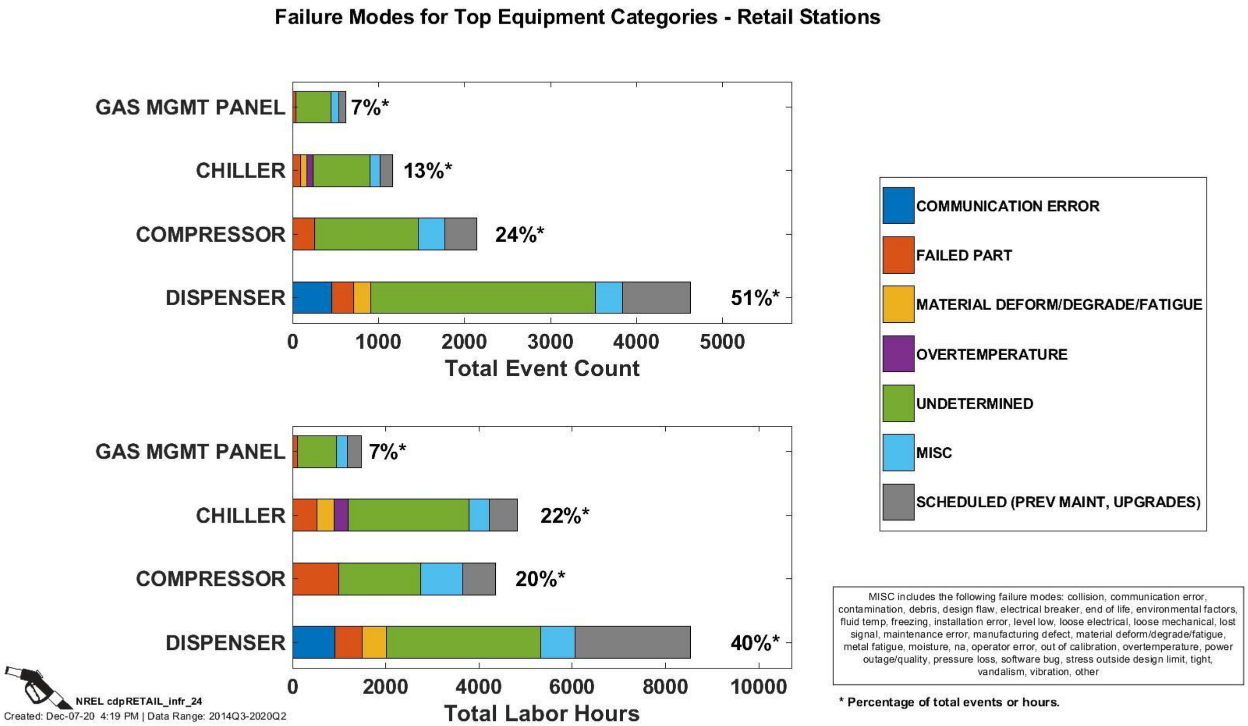


Figure 11 Data from NREL showing a mixture of partially defined failure causes for equipment categories at retail stations [63]

NREL presents these CDPs at various conferences and to the Department of Energy (DOE) to influence funding and the development of research areas for hydrogen stations. In published literature, NREL's CDPs are used as a reference point and those with access to the raw data use it as a reliability data source. A paper by Samuelsen et al. (2020) uses CDPs regarding failure rates per fill and failure causes for components to determine how the hydrogen station at the University of California Irvine is performing compared to other US stations [64]. A study by Kurtz et al. (2020) uses data from maintenance and fill logs, that is not publicly available, to perform a Crow-AMSAA reliability growth model [65]. This provides a quantitative understanding of hydrogen fueling station system failure with the ability to predict failures and evaluate the success of reliability improvement plans [66]. NRELs CDPs can be used as a benchmark for generic hydrogen fueling station data or to trend data over time. While the raw data is quantitative and could be used for basic risk assessment, it lacks a formal classification of failure modes for each component and thus cannot be used for rigorous QRA.

3.1.3.4. CHS Data collection tool

CHS is currently developing a hydrogen equipment and component failure rate data submission tool [67]. The purpose of this tool is to develop failure rates specific to hydrogen components to improve QRA for hydrogen fueling stations. CHS member companies would report on a schedule to track station performance. CHS intends to process this raw data into failure rates to maintain the anonymity of reporting companies.

The data to be collected by this form is related to system failures that are defined exclusively as a leak. Given that there is a leak, the form collects information about the equipment, fitting, hydrogen state, consequence, system response, and corrective action. A complete list of data entry fields is presented in Table 7. The data fields are a combination of open-ended quantitative fields and predetermined lists. The form is designed to be user friendly with intuitive prompts and short lists to choose from. Some data fields would benefit from having a description to remove ambiguity for the user, for example, “number of like components in service” needs a definition of what like means. This could mean something as vague as how many other valves or as specific as how many other manual ball valves operating at 700 bar.

Number of like components is an important piece of data to collect but it should be more clearly defined to ensure standardized reporting. Also, the predetermined components are generalized and do not consider the location within the system or operating conditions. Additionally, failure mode and mechanism data are not collected. This is particularly important because the hydrogen industry needs component failure rates attributed to specific failure modes and mechanisms. Finally, the component age/operating hours/demands is not recorded but would be useful to determine component failure rates. Once developed, the CHS data collection tool will present a step forward in quantitative data collection. The previously mentioned data gap and the lack of a formal failure mode taxonomy leave a need to develop a more thorough/complete hydrogen reliability data collection tool.

Table 7 CHS failure rate data entry fields

General information	**Failure**
Application	Date of failure
Facility name	Equipment type
Facility area	Fitting type
Operating time since last report	Component service type
Leak/No leak record	H_2 state for component
	Isolatable?
	Was leak confined?
	Upstream pressure
	Pipe/tube size
	Number of like components in service
	Leak flow rate estimation
	Leak detection method
	System response to leak
	Did leak ignite?
	Corrective action
	Downtime because of leak
	Lost mass
	Flow rate

3.1.4. Result: Critical analysis of H2 data collection tools

H2Tools and HIAD are safety databases that fill a need to document accidents and share lessons learned within the hydrogen community. NREL is a reliability data collection tool but the underlying data being collected is not public, and the NREL CDPs created from this data do not synthesize the data into a quantitative product that is useable for QRA. Once developed, the CHS data collection tool could improve the collection of quantitative data but requires further development to be useful to QRA. This section will discuss areas of strength and weakness across all hydrogen safety data collection tools.

The data collection tools have core strengths consistent with their experience in capturing the context of failure events. Initiating event, failure root cause, and incident severity data is consistently collected. Release size data can be found completely in HIAD and CHS data collection tool, and partially in NREL CDPs grouped as small, audible, or gross. All databases contain at least partial consequence data including some combination of number of injuries, fatalities, property loss, downtime, and legal actions, with the most complete consequence data being found in NREL CDPs and HIAD. All the data tools, except for NREL CDPs collect data on any hydrogen related event or system, while the NREL data examined is specific to hydrogen fueling stations. The data is consistently presented anonymously by all these tools.

Due to the differing intentions of these data tools some excel in unique areas, discussed in this paragraph. NREL CDPs is the only database that comes close to adequately capturing the location of the failure within its respective subsystem. HIAD records “systems involved” in accidents but it is an open-ended data field which results in inconsistent and incomparable data. NREL is the only tool that collects operations, maintenance, and site inventory data. This includes information related to fueling, fill performance, dispensing, and compression during normal operation. A complete log of preventative and corrective maintenance data is collected for specifically identified parts. Site inventory data is collected for components in production, compression, dispensing, and storage including diagrams and operating conditions. CHS collects partial operation data, but only to identify the time since the last status report and whether there has been a leak. In terms of maintenance, CHS records whether the type of corrective action was tightening, rebuilding, or replacing. CHS collects no site inventory data other than the number of "like components" in service to the one that failed. The term "like" here needs to be better defined for reporters to understand the level of specificity. H2Tools and HIAD are the only tools that provide public access to the data reports. The CHS tool has not been released yet, so the level of public availability is unknown at this time, but it is unlikely that the direct reports will be publicly available due to private reporting agreements with commercial stations. NREL and CHS are the two data tools that have relationships directly with stations and receive regular reports, allowing for more consistent report quality while the other tools have many data fields missing from reports. HIAD is the only tool with transparent documentation of the motivation, database structure, data collection, definitions, and data dissemination [45].

Aspects of data collection related to failure modes, system breakdown, and component life/usage are consistently missing across the industry. Notably, none of the surveyed tools collect failure mode or failure mechanism information. NREL collects some data on failure causes including failure modes, failure mechanisms, and influencing factors, but since they are undefined and non-exhaustive, they cannot be considered formal failure modes and mechanisms. Component life is also not collected anywhere across industry, but is essential to develop failure probabilities. NREL collects information on number of fills and amount of hydrogen dispensed at each station and uses this to compare failure rates. This is useful quantitative data, but is not specific enough to obtain failure rates for individual components. Occurrence and amount of hydrogen accumulation in the event of a release is not collected by any tools and is needed to develop a complete understanding about consequence and system response. CHS is the only tool that partially collects data on system response and hydrogen detection, but this data is limited to what the release detection methods was and whether or not the system shut down automatically, shut down manually, or was manually isolated.

The data collection tools described above have been compared side by side in

Table 9 to show areas that are currently being collected and those that still need to be developed. The green checked boxes indicate adequate data collection, yellow boxes with Os indicate partial data collection, and red boxes with Xs indicate no data collection. Here partial data collection means that the tool is collecting some data related to that data type but it is not sufficient to produce rigorous hydrogen reliability data. The grey boxes with question marks indicate fields that are unknown at this time since the CHS tool has not yet been published. This comparison is not intended to point out flaws with data collection tools; it is only meant to show where data is being collected. It is understood that these tools have been designed to collect only certain types of data.

Table 8 Key for review of current hydrogen safety data collection tools

Data collection key	
Complete	✓
Partial	O
Unknown	?
None	×

Table 9 Review of current hydrogen safety data collection tools

Data Type		H2Tools	NREL CDPs	HIAD	CHS Failure Rate Data
Event and failure characterization	Initiating event (description)	✓	✓	✓	×
	Location within system	×	✓	O	×
	Failure mode	×	×	×	×
	Failure mechanism	×	×	×	×
	Failure root cause	✓	✓	✓	×
	Release size	×	O	✓	✓
	Incident severity	✓	✓	✓	✓
	Consequences	O	✓	✓	O
	System response (Mitigation)	×	×	×	O
	H2 accumulation	×	×	×	×
	H2 detection	×	×	×	O
Life/usage	Component life	×	×	×	×
	Operations	×	✓	×	O
	Maintenance	×	✓	×	O
	Site inventory	×	✓	×	O
Data scope	Public access to data	✓	×	✓	?
	Scope includes any H2 incident	✓	×	✓	✓
	Regular reporting	×	✓	×	✓
	Anonymous data presentation	✓	✓	✓	✓
	Data quality checks	×	✓	×	?
	Process documentation	×	×	O	×

To create a data collection framework following best practices, all of these data types and characteristics of collection as identified in Table 9 must be accounted for. A reliability database based on this framework will generate hydrogen reliability data including component failure, detection, and isolation rates specific to hydrogen fueling station components that is useable for QRA.

3.1.5. Data: System reliability data collection best practices

After reviewing the current state of hydrogen reliability data collection, a review of reliability data collection best practices found that the OREDA is the most well-developed and widely used reliability database that is applicable to the hydrogen industry. OREDA collects offshore and onshore oil and gas reliability data so the approach used for data collection can be applied to the hydrogen industry. However, OREDA data cannot be used in place of hydrogen specific reliability data because oil and hydrogen have very different properties and oil production platforms and hydrogen fueling stations are very different systems. OREDA data collection strategies are presented in this section.

OREDA was developed in 1981 with the goal of creating reliability data for safety equipment specific to offshore oil and gas [68]. Prior to OREDA, there was no centralized offshore reliability data and risk assessments were made using generic onshore data and data from other industries [69]. The database is populated by a collection of oil and gas companies that report their failure and operation data, and can utilize the collected data to improve company and industry reliability practices. Each piece of equipment is rigorously defined and broken down into a collection of maintainable items. This data is also aggregated into equipment failure rates broken down by failure mode, mechanism, and severity. These failure rates are available to the public for purchase and are frequently used in QRA.

OREDA collects site inventory data, maintenance data, and failure data from all member companies. Site inventory data consists of a hierarchy for each site that decomposes the system into, equipment unit, subunit, and maintainable item. The data collection requirement for member companies is not public so it is unknown to what extent the entirety of data is collected, however based on the description in the OREDA handbook, site inventory data includes technical data (e.g. capacity, size) and operating and environmental data (e.g. operating mode, vibrations) for each equipment item [70]. Each equipment item also has a boundary diagram to establish what subunits are included in that equipment item. Any failure or maintenance events that occur are attached to the specific equipment unit they belong to within the hierarchy. The failure data describes the characteristics of the physical failure including failure mode and cause. Maintenance data includes a description of any corrective or scheduled maintenance.

The OREDA handbook is the publicly available data product from this database and sets the standard on what reliability data collection should look like [70]. This data is sanitized, aggregated, placed in data fields outlined in Table 10, and processed into reliability data. For each equipment unit there is a list of failure modes by severity class, aggregated observed time in service, observed number of failures, estimated constant failure rate for each failure mode with uncertainty intervals, mean and maximum active repair time, mean and maximum manhours repair time, and equipment population. In addition, there are cross tables comparing maintainable item vs. failure mode and failure mechanism vs. failure mode. Data tables are presented for generic equipment categories such as compressor and broken down to more specific design classes for each type of equipment such as “100-1000kW electric centrifugal compressor”. Failure rates are presented as total combined failure rates and then broken down by failure mode at each level of severity. Additionally, failures are described in cross tables by failure mode and failure cause. This data allows for component failure data to be filtered and extracted based on a variety of different characteristics making them useful for QRA. The data collection and analysis approach is completely documented in the OREDA handbook and includes scope, organization, data structure, estimation procedures, data table formats, definitions, and limitations.

Table 10 OREDA Handbook data table fields

OREDA Handbook data table fields
Taxonomy number and item
Population
Installations
Aggregated time in service
Number of demands
Failure mode
Failure cause
Number of failures
Failure rate
Active repair time
Repair time (manhours)
On demand failure probability

The primary limitations of OREDA is that is does not collect data on gas stations, meaning the data cannot be used as a substitute for hydrogen specific reliability data. Also, the failure modes are not defined in the documentation. Including failure mode definitions in the context of oil and gas is important for the standardization of data collection and data use. In addition, Data from each member company has been kept anonymous so all data presented is generic and failure rates are a weighted average based on the installations they are reported from. The scope of the database is limited to collecting failure and maintenance data on hardware equipment and while human failures are implicitly included in the data, metrics specific to human failures are not generated.

3.2. Task 2: Hydrogen reliability data collection framework requirements

3.2.1. Result: Requirements of the database

The requirements of a hydrogen reliability data collection framework are determined based on QRA data needs, current hydrogen safety data collection tools, reliability data collection best practices. These requirements are presented here as a result of Task 2. The missing piece of hydrogen reliability data that this tool seeks to fill is highly quantitative data at the system and component level as shown in Figure 12. Hydrogen physics models are adequately developed for use in QRA at the highly quantitative level, while system and component level data are lagging behind. The requirements described here include characteristics of the database and the types of data that will be collected. This purpose is to ensure the collection of high quality, objective, hydrogen reliability data that can be used to generate probabilities for use in QRA and reliability engineering, not just sharing lessons learned from safety events.

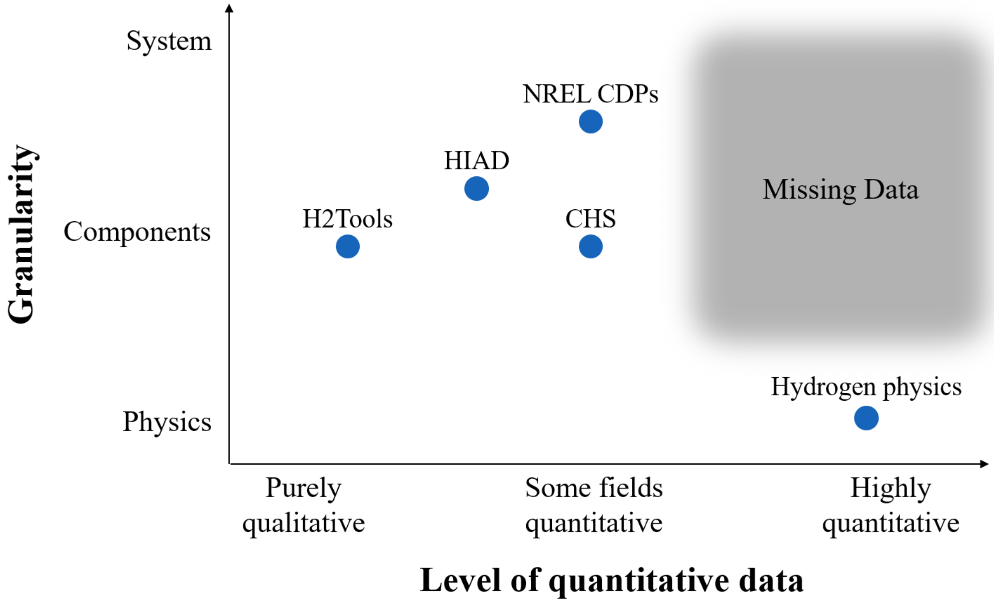


Figure 12 Current data and research focus in the hydrogen industry

The following are the characteristic requirements of the database:

C1. Design for non-expert end users: Those reporting will be from industry and may not be familiar with the data collection form. Clear instructions and definitions are needed to enable quick, accurate input that is standardized across all parties reporting.

C2. Publicly available: The data must be turned into probabilities and frequencies that are publicly available to be used in QRA and reliability engineering for all users.

C3.Regular reporting: The participating stations must report all of their failure and maintenance events on a regular basis to guarantee collection of all failure and maintenance events as well as time without failures and maintenance.

C4.Anonymity: Anonymity must be ensured in public presentation of results to encourage unbiased reporting.

C5.Quality assurance: Reports must contain all required information to prevent gaps that would compromise the quality of the derived estimations. The quality of the data collected should be reviewed to ensure completeness and accuracy before being used in estimates.

C6.Regular updating: The data collection tool and any derived estimates should be updated regularly to reflect any changes in available data and keep up to data with best practices.

C7.Process documentation: Transparent documentation of the motivation, scope, data structure, definitions, and methodology for reporting and updating should be available to the public.

The other requirements for a data collection framework are the types of data that need to be collected. As presented in Figure 10, there are multiple types of data that are useful to QRA but they can broadly be described in two categories: static and event data. Static data, on systems and facilities, does not change over time. Event data, such as frequencies and consequences, are occasional occurrences. The data collection framework must include both static and event data in order to develop component failure rates that account for operating conditions and censored data.

The following are static data requirements of the database:

S1. Component location: The location of the failed component within the system provides information regarding the relationship between component function and system failure.

S2. Operating conditions: Collection of operating condition data is required to understand the relationship between operating condition and failure rate. Current component failure data do not account for operating conditions so the effect is unknown at this point.

S3. Component life: Collecting data on component age, operating hours, and/or demands (whichever is relevant to the component) is essential to develop failure probabilities with respect to component life.

S4. Number of like components: The other components that have not failed act as right-censored data to adjust the failure probability for that component. A definition of "like components" must be provided with the data collection tool.

There are three types of event data that will be collected: failure data, preventative maintenance data, and corrective maintenance data. Event data must be collected at the component level to capture the different operating conditions specific to each subsystem which can affect component behavior and failure rates, as pictured in Figure 13. This will be facilitated by a validated system hierarchy specific to hydrogen fueling stations.

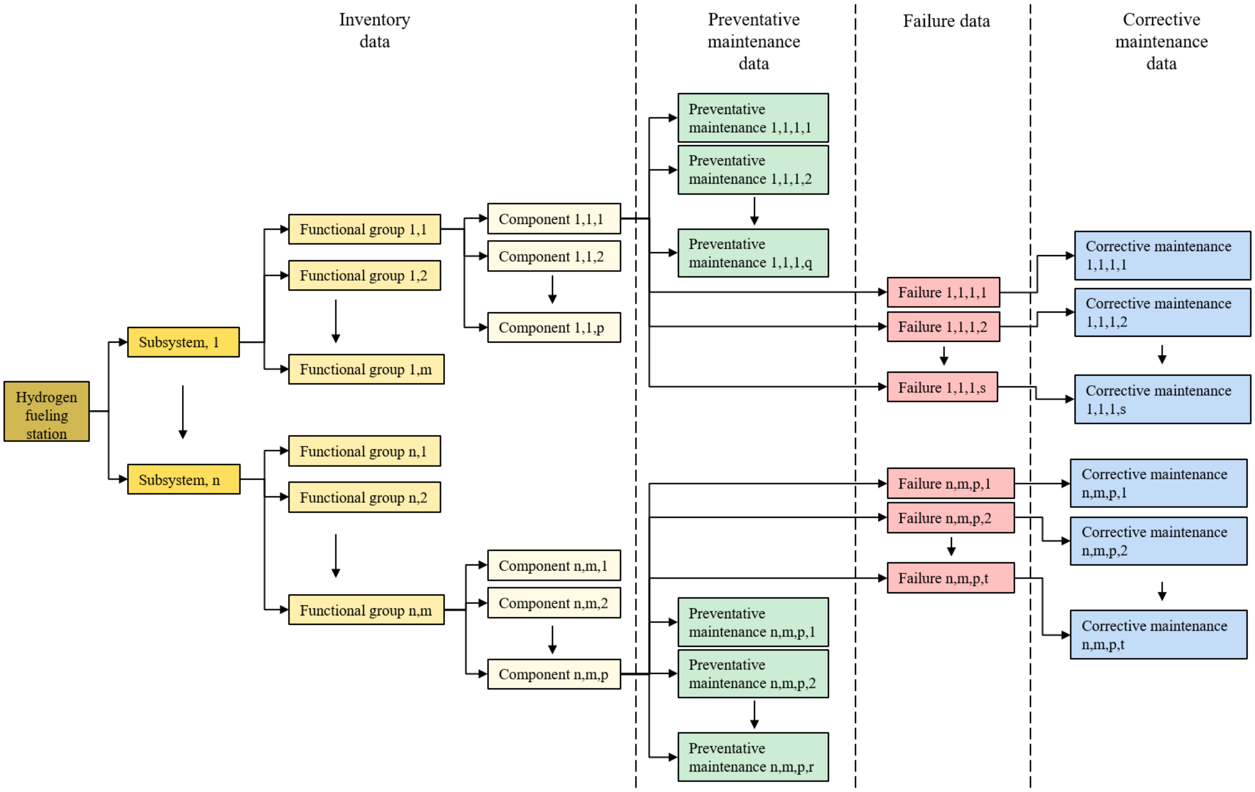


Figure 13 Data collection hierarchy framework

The following are event data requirements of the database, specific to failure events:

E1. Narrative event description: Captures details that cannot be collected with quantitative data or predetermined data fields. Includes description of the initiating event which will be used to inform FMEA and ESD.

E2. Failure mode, mechanism, and root cause: Shows how and why equipment is failing in order to develop failure rates by failure mode, appropriate mitigation strategies, and inform FMEA.

E3. Release location and size: (Where failure results in a release). This can be used in combination with the system pressure to estimate flow rate and release over a given period.

E4. Hydrogen accumulation: For hydrogen fueling stations this is typically hydrogen accumulation in the form of gas or liquid pooling, ignition, delayed ignition, explosion, or dispersion. Accumulation data is used to determine whether detection has occurred appropriately and the risk potential. This data will be used to inform probabilities within the ESD.

E5. Detection: In the event of a release, data must be collected about whether the system detected the release or flame. Detection data includes gas and flame detection sensor operation, proximity to release or fire, and time before detection. This data will be used to inform probabilities within the ESD.

E6. Isolation: How the system responds to the failure must be recorded, including isolation valve operation, time before operation, and effectiveness. Also, whether the system operated automatically or required manual shutdown/isolation. This data will be used to inform probabilities within the ESD.

E7. Consequence: A specific description of human, property, and/or environmental losses that result from the failure. This also includes downtime and labor costs that will be reported with maintenance.

E8. Severity: Describes the effect of the failure on operational status and therefore the effect on the risk of fires and explosions. A well-defined quantitative scale will need to be developed in order to standardize severity reporting.

The following are event data requirements of the database, specific to maintenance events:

E9. Type of maintenance: For example, predictive, condition-based, scheduled, or corrective maintenance.

E10. What was performed: For example, repair, replace, tighten, relubrication.

E11. Active repair time: Time duration in which actual repair work is being performed. This is part of failure or maintenance consequence.

E12. Manhours: This includes the active repair time as well as durations of rundown, delays to issue work orders and wait for repair personnel or equipment, and start-up. This is a part of failure or maintenance consequence.

These requirements describe the gold standard of reliability data collection for hydrogen fueling stations. It is likely that not all this data will be available at the same level of precision for each failure event so the next step will be working with industry to determine what types of data they can collect and aligning a data collection tool with what they can provide. This will allow for consistent, complete reporting and the development of quality reliability data to support rigorous hydrogen fueling station QRA.

3.2.2. Anticipated users & usages

The database framework described by the requirements in Section 3.2.1 is intended to create a data product that is useable for the hydrogen community. This will be done by incorporating these data collection procedures into already established tools like NREL's CDP project. The data that is produced will be incorporated into current hydrogen QRA tools such as HyRAM and can be used by other groups studying hydrogen system risk.

The current HyRAM reliability data comes from work done by LaChance in 2009 [8]. This used Bayesian updating to combine component failure rate data from the offshore petroleum, nuclear power, natural gas, and chemical processing industries with hydrogen specific data provided by CGA in order to develop component failure rates for generic hydrogen system components. The other industry data was used as prior data because there was no hydrogen specific component failure rate data available. It was determined that components from these industries would fail in similar ways and could act as a starting point for estimating hydrogen component failure rates. However, hydrogen specific failure data should be used as well to capture the effect of hydrogen specific failure mechanisms such as embrittlement. This model is updated with hydrogen specific data and develops a posterior distribution of component leak rates based on all of the data in the model. Bayesian updating is a useful tool because the model can be updated any time new data is available. The previous posterior distribution becomes the prior, new data points are added and then the model generates a new posterior distribution. As more high-quality data is added to the model, the uncertainty will be reduced and the posterior distribution of leak frequencies will have a smaller range.

In 2020 Glover, Baird, and Brooks used the same Bayesian updating process to develop hydrogen component leak frequencies for hydrogen production plants. The model was first updated with generic data and then updated again with hydrogen specific failure data [71]. Bayesian updating was also used by Ehrhart and Brooks in 2020 to determine leak frequencies for liquified natural gas (LNG). Generic data from other industries was combined with data from LNG in order to estimate leak rates [72]. As HyRAM was looking for data to quantify leak frequencies for LH2 the lack of available data led to the use of this LNG data as a proxy for LH2. This project plans to update the model with LH2 data in the future, to develop more refined leak frequency distributions [73].

The data gathered by this hydrogen system reliability data collection tool is intended to update the Bayesian models. This means that all of the previous data will continue to be used as a prior, but new hydrogen system reliability data can be introduced to develop more accurate leak frequencies for hydrogen systems. The data can also be used for research purposes to get a better idea of how hydrogen fueling stations are failing and what areas need work to improve safety.

3.3. Task 3: Data collection framework for hydrogen fueling station QRA

3.3.1. Generic component hierarchy

To collect quality reliability data across hydrogen fueling stations, a generic component hierarchy is needed to standardize system description. Currently, there is no hydrogen specific component reliability data being collected to support QRA. The data being used has been created for hydrogen components based on similar industries and does not consider system function or operating conditions. Creation of a generic component hierarchy for hydrogen fueling stations will structure data collection in a way that inherently considers system and subsystem function and operating conditions. The hierarchy developed in this section to fills the hydrogen-specific data knowledge gap discussed in Section 2.3.1.

3.3.1.1. Method: System decomposition approaches

Sources that list hydrogen fueling station components and piping and instrumentation diagrams (P&IDs) that are publicly available are very scarce. A representative set of publicly available sources that describe hydrogen fueling station components have been collected from technical reports and journal articles. The six stations reviewed come from Honsellar (2018) in the Netherlands, Suzuki et al (2021) in Japan, and the H2FIRST project (2015) and (2020) in the US [10], [23], [74], [75]. Each station is decomposed down to the component level to determine how the hierarchy should be structured. These designs in combination with expert knowledge are used to inform the development of this hierarchy. There are three traditional methods for system decomposition: assembly, functional, and service-based. These methods are described to determine their applicability to hydrogen fueling station decomposition and a new method is developed to fit the needs of this project.

Assembly decomposition

Assembly decomposition is a method in which a system is broken down by what items can physically be separated. Big sections that can easily be removed from the larger system make up the first level of the decomposition. Then each big section is separated into smaller sections that can be easily separated from the bigger section. This process is continued until the desired granularity is reached [76]. To perform an assembly-based decomposition the product or system is physically disassembled by hand or with modeling software. Assembly decomposition lends itself to manufacturing processes where a product is assembled in stages. This method would be used in a situation where the user wants to ensure the product is composed of similar sized assemblies to keep a balanced work flow throughout the manufacturing process [77].

Functional decomposition

Functional decomposition is a method that breaks down a system by the different functions it performs [76]. Each function is made up of subsystems which can then be further decomposed by function until the desired level of granularity is reached. Unlike assembly decomposition, the location of the components does not matter to functional decomposition. For example, the instrument air/ nitrogen subsystem will be present across the entire larger system (multiple functions) but is its own subsystem. Functional decomposition lends itself to the design process as it is common for design teams to be divided by function, for example building design teams could be divided into mechanical, electrical, plumbing, fire protection, and structural.

Service-based decomposition

Service-based decomposition is a method that breaks down systems by how maintenance is performed on them. This is the way that the service manuals are constructed to provide guidance to owners or field technicians who will be working on the system in the field [76]. Any component or subsystem that requires unique maintenance should be separated from the rest of the system to provide specific guidance to the user. This decomposition method is harder to describe because it will look different for different systems. Some may break down the system by how frequently each component requires maintenance or by what type of skill sets or tools are required to perform the maintenance [77]. This is a unique method that focuses on the system while it is in operation as opposed to while it is being designed.

Blended decomposition method for hydrogen fueling station

The goal of the decomposition of hydrogen fueling station designs is to be able to create a generic component hierarchy. System decomposition literature is reviewed to find a description of similar processes. The review finds decomposition methodologies to increase manufacturing process and equipment health awareness [78], a tool for quantitative assessment of product architecture [79], and a case study of system decomposition methods on a Xerox printer [76], but none offer guidance on how to perform a generic system decomposition. A new method of decomposition must be designed to make a hierarchy that will be used for the collection of hydrogen reliability data.

Thinking about system decomposition from a risk and reliability perspective adds another level of complexity to this project. Hollnagel, the developer of the Functional Resonance Analysis Method, a method to model and analyze socio-technical systems providing a basis for risk assessment, proposes the use of functional descriptions of systems in order to improve risk assessment. Current risk assessment is performed without consideration of the full behavior of the system. By capturing system function, risk assessment can reveal the system’s ability to detect, respond, learn, and anticipate. This requires a shift in viewing safety as something a system does rather than something it has [80]. This method of thinking is an important step for the hydrogen industry to adopt, but it does not lend itself to reliability data collection because it ignores the specific location of the component within the system in favor of component function. In order to comprehensively characterize the system and collect reliability data, functional decomposition must be blended with service-based decomposition. A blended hierarchy allows for the collection of failure and maintenance data on all components in their respective locations within the system while also collecting data on component function within the system. This is achieved by having levels of abstraction that describe subsystems and components (service-based decomposition) as well as functional groups (functional decomposition).

3.3.1.2. Data: Representative set of hydrogen fueling stations

Due to hydrogen fueling stations being run by private companies, it is difficult to find station P&IDs. However, it is possible to collect a representative set of designs to inform a generic hydrogen fueling station system decomposition. The representative set of stations chosen for this project are publicly available, not specific to any company, geographically varied, and developed by internationally recognized engineering research labs.

The chosen station designs include a 300kg/day gaseous delivery station and a 300kg/day liquid delivery station designed by the Sandia and NREL teams working on the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project [74]. Two more station designs are generic 600 kg/day gaseous delivery and liquid delivery stations designed as part of the same H2FIRST project [75]. These stations use a modular design so the bulk storage systems are different but all of the other systems are the same. Another representative model of a Japanese gaseous hydrogen fueling station from Suzuki et al. (2021) that was developed by reviewing existing designs and through interviews with related companies [23]. The last is a text-based description of subsystems, components, and configurations of all 15 gaseous hydrogen fueling stations in the Netherlands [10]. All designs except the text-based description are present in Appendix A.

3.3.1.3. Method: Decomposition of hydrogen fueling stations

Each of the six representative stations is decomposed with the intention of creating a hierarchy that blends functional and service-based decomposition. The first level of decomposition is by subsystem as separated by double block and bleed valves. This is both a functional decomposition, as each sub system performs a different function, and a service-based decomposition because these double block and bleed valves are used to isolate separate subsystems to perform maintenance. The results of this decomposition for each representative station are presented in Table 11. The components within each subsystem for each representative station are then listed. These tables can be found in Appendix B. The Netherlands hydrogen fueling station source includes information about onsite hydrogen production but the scope of this project is limited to delivery of hydrogen. The organization of components that results from this decomposition is used to make a generic component hierarchy for hydrogen fueling stations.

Table 11 Representative hydrogen fueling station subsystem decomposition

Subsystems					
Netherlands stations [10]	**Japanese station** [23]	**US 300 kg/day liquid station** [74]	**US 300 kg/day gaseous station** [74]	**US 600 kg/day liquid station** [75]	**600 kg/day gaseous station** [75]
Natural gas reformer	Trailer	Bulk liquid storage	Tube trailer gaseous storage	Bulk liquid storage	Gaseous storage cylinders
Water electrolyzer	2-inch pipe	Compression	Compression	Compression	Compression
Hydrogen pipeline	Intermediate cylinders	Cascade storage	Cascade storage	Cascade storage	Cascade storage
Tube/cylinder trailer	Compressor	Instrument air	Instrument air	Instrument air	Instrument air

Compressor/booster	Cylinders	Chiller	Chiller	Chiller	Chiller
Buffer storage	Dispenser	Dispensing	Dispensing	Dispensing	Dispensing
Pre-cooler/heat exchanger					
Dispenser					

This naming structure for the generic component hierarchy is determined from traditional systems engineering practices and examining naming conventions for hierarchies in other industries. In systems engineering the standard naming structure for system levels of abstraction is presented in Figure 14 [81]. This comprehensive structure is meant to be tailored to the system of interest by removing levels that don’t apply and stopping at the appropriate level of decomposition for that system. Many of these levels map well to the decomposition of hydrogen fueling stations, however the hierarchy developed for hydrogen fueling stations is not the description of one system, but is a generic component hierarchy meant to represent all publicly available hydrogen fueling station designs. This means that the components in each level don’t neccesarily combine to form the level above. All of the components needed to form the level above are present but there are additional components as well, due to the need to represent a variety of system designs. This created a naming challenge because terms like “assembly” no longer apply. Instead, a naming structure with four levels of abstraction and the potential future addition of two more levels is proposed in Figure 15. These six levels of abstraction are defined in Table 12.

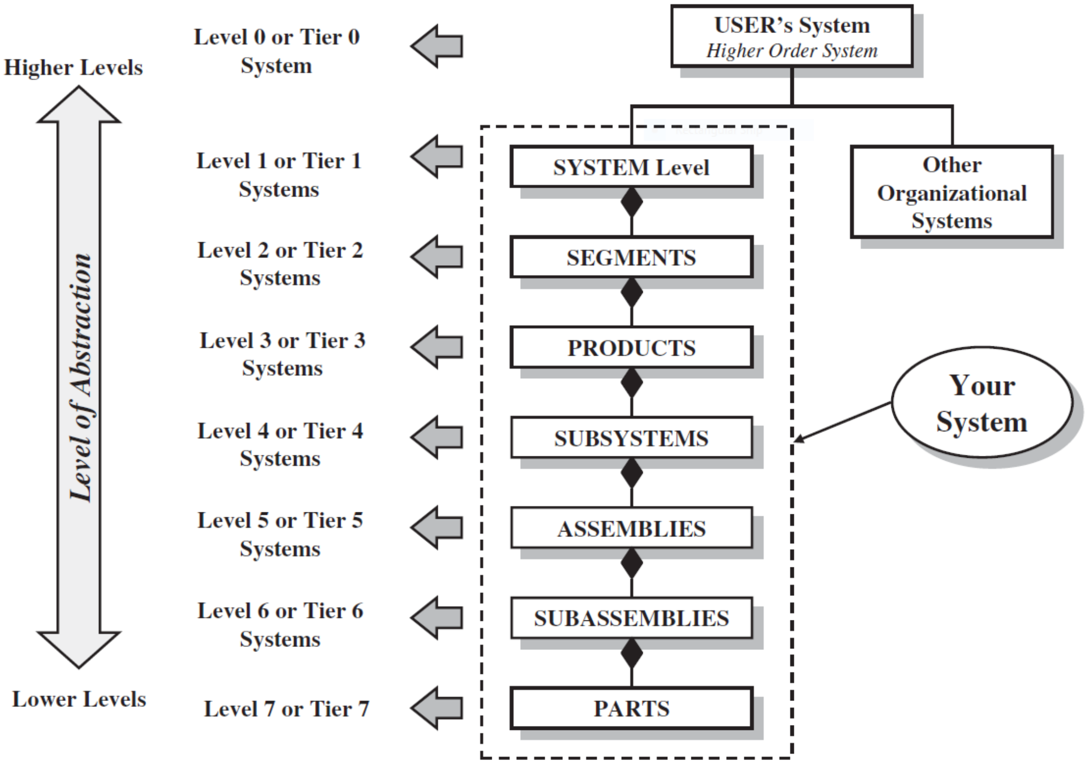


Figure 14 System Engineering Levels of Abstraction [81]

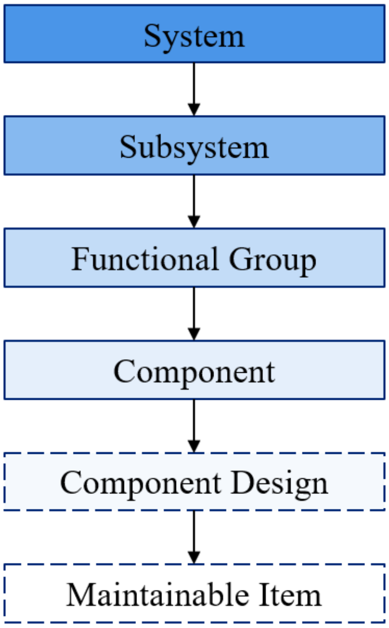


Figure 15 Hydrogen fueling station generic component hierarchy levels of abstraction

Table 12 Hydrogen fueling station hierarchy levels of abstraction definitions

Level	Nomenclature	Definition
1	System	Combination of elements that function together to produce the capability required to meet a need
1.1	Subsystem	An independent system operating as a part within a larger system
1.1.1	Functional Group	A collection of individual components that support the same function
1.1.1.1	Components	The lowest level generic parts considered for hydrogen reliability data collection
1.1.1.1.1	Component Design	Specific designs for components identified in 1.1.1.1
1.1.1.1.1.1	Maintainable Item	Lowest level maintainable items on which hydrogen reliability data could be collected

3.3.1.1. Result: Hierarchy levels of abstraction and nomenclature

The first level, 1, is System, which is defined by NASA as a combination of elements that function together to produce the capability required to meet a need [82]. The second level, 1.1, is Subsystem, which is defined as an independent system operating as a part within a larger system. The third level, 1.1.1, introduces a new term, Functional Group, which is defined by this thesis as a collection of individual components that support the same function within a subsystem. This unique level is required because the standard systems engineering semantics are not flexible enough to describe a generic hierarchy that encompases the components of multiple hydrogen fueling station designs. Level 1.1.1.1, is Component, which is defined by this thesis as the lowest level generic parts considered for hydrogen reliability data collection.

There are two additional levels that may be added in the future, 1.1.1.1.1 Component Design and 1.1.1.1.1.1 Maintainable Items. The component design level would allow data collectors to expand upon the generic components listed in the hierarchy into specific components with different designs. For example, the component designs for a heat exchanger could be coaxial tubes, shell and tubes, or cold metal blocks. The maintainable item level would allow for the collection of data on items within the components. For example, some maintainable items for a coaxial tube heat exchanger could be tubes, seals, shell, power supply, and wiring. This may be especially useful for individual hydrogen fueling station data collection because it can include all the specific components onsite and continue the hierarchy to the lowest level of items that are maintained.

3.3.1.2. Result: Generic component hierarchy

The hierarchy developed in this thesis blends functional decomposition with service-based decomposition in order to capture the function of the system as well as all of the necessary components for hydrogen reliability data. The uniqueness of hydrogen fueling station designs merits this change from standard system decompositions. The benefits of this blended decomposition are its intuitiveness and ability to support risk assessment. Having functional groups allows non-expert end users to easily find components relevant to their needs while the exhaustive list of components is a feature of the service-based decomposition. This blended decomposition allows us to understand component failure in the context of system functions and separate these failures by operating conditions. This is critical to perform process-based risk assessment with full understanding of system behavior and interactions between system functions and system response as a whole. The generic component hierarchy for hydrogen fueling stations is presented in hierarchy Figure 17 a-g, as well as a larger version in Appendix C.

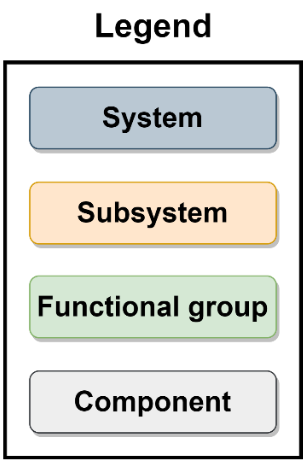


Figure 16 Generic component hierarchy legend

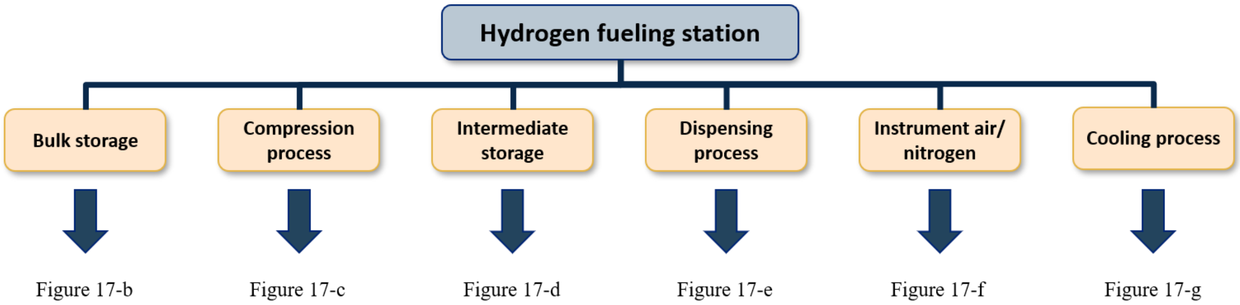


Figure 17- a Generic component hierarchy subsystems

The hydrogen fueling station is split into six subsystems that naturally separate at their double block and bleed valve. Each performs a different function: bulk storage, compression, intermediate storage, dispensing, instrument air/ nitrogen, and cooling. These subsystems all have the potential for different operating conditions. Pressure and temperature vary throughout an individual hydrogen fueling station and vary across different hydrogen fueling station designs. This necessitates that hydrogen reliability data include the subsystem location, to differentiate operating conditions and also to understand failures in the context of system functions. Subsystems are independent sets, meaning the failure of one does not influence the functional failure of another; however, it would influence the failure of higher levels of the hierarchy. This is designed to inform event tree analysis.

This hierarchy design means that components are duplicated across different subsystems and functional groups in order to inherently capture their operating conditions and function within the system. The downside of this is that it divides components and may reduce the amount of data that is collected on each type of component. The more data there is the more accurate component failure rates will be. It is important to note that this component data can be recombined in order to have a larger sample size of failures. This can be done by cross-linking the components in the backend of the database software and will not be the burden of the user. The hierarchy is structured in this way because component data collected all together cannot be divided by operating condition later but it can be recombined at any time.

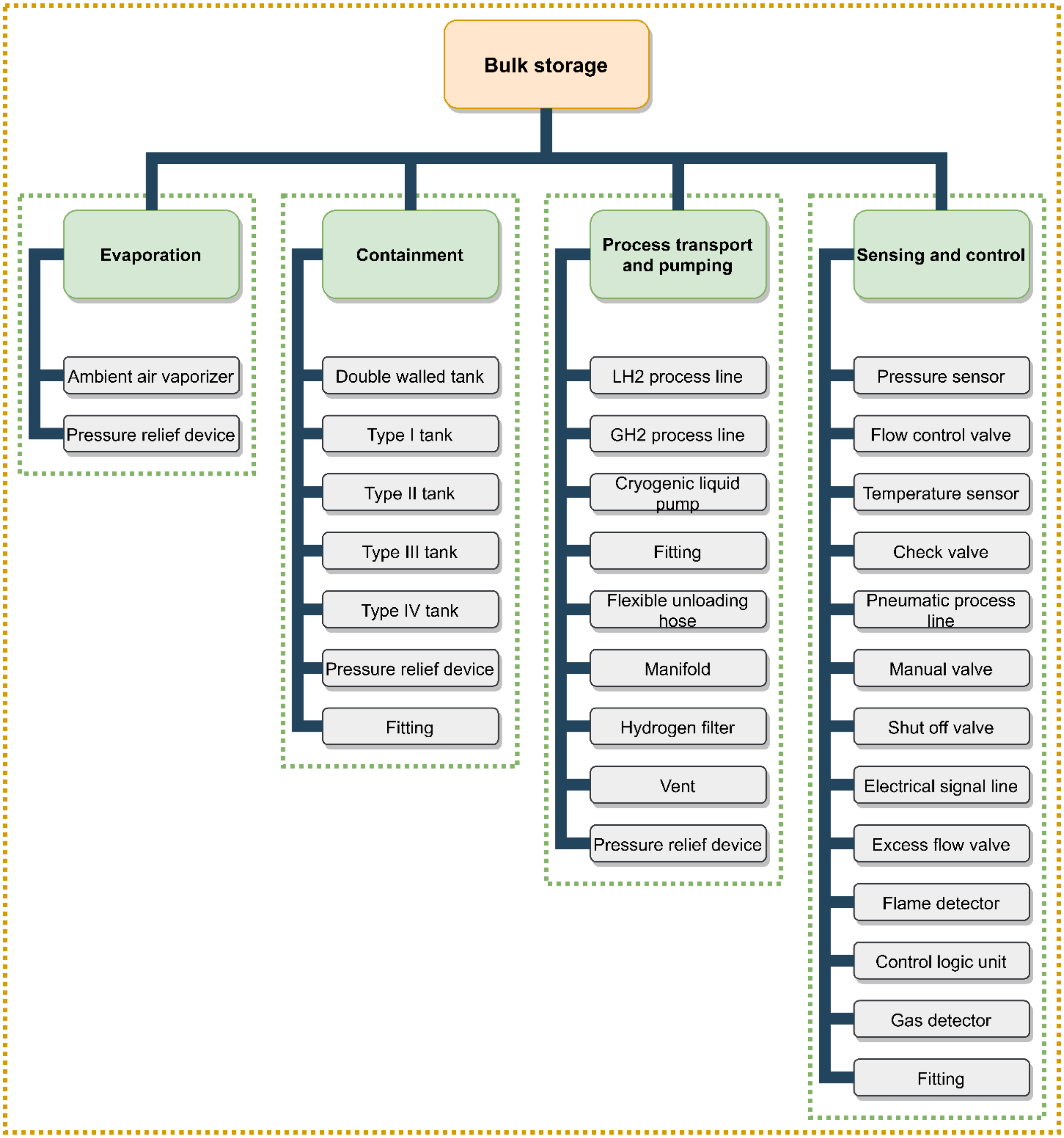


Figure 17- b Generic component hierarchy bulk storage subsystem

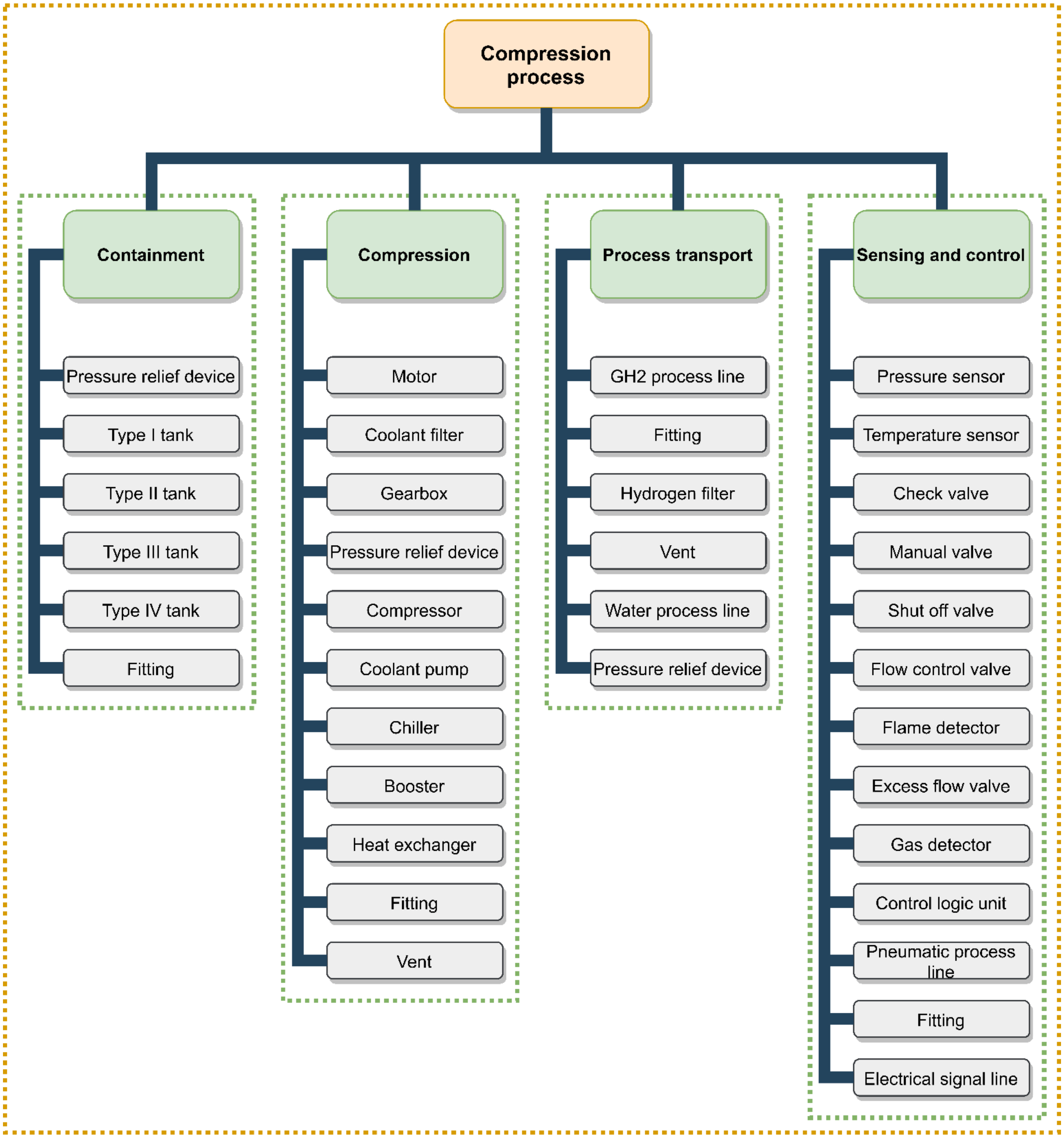


Figure 17- c Generic component hierarchy compression subsystem

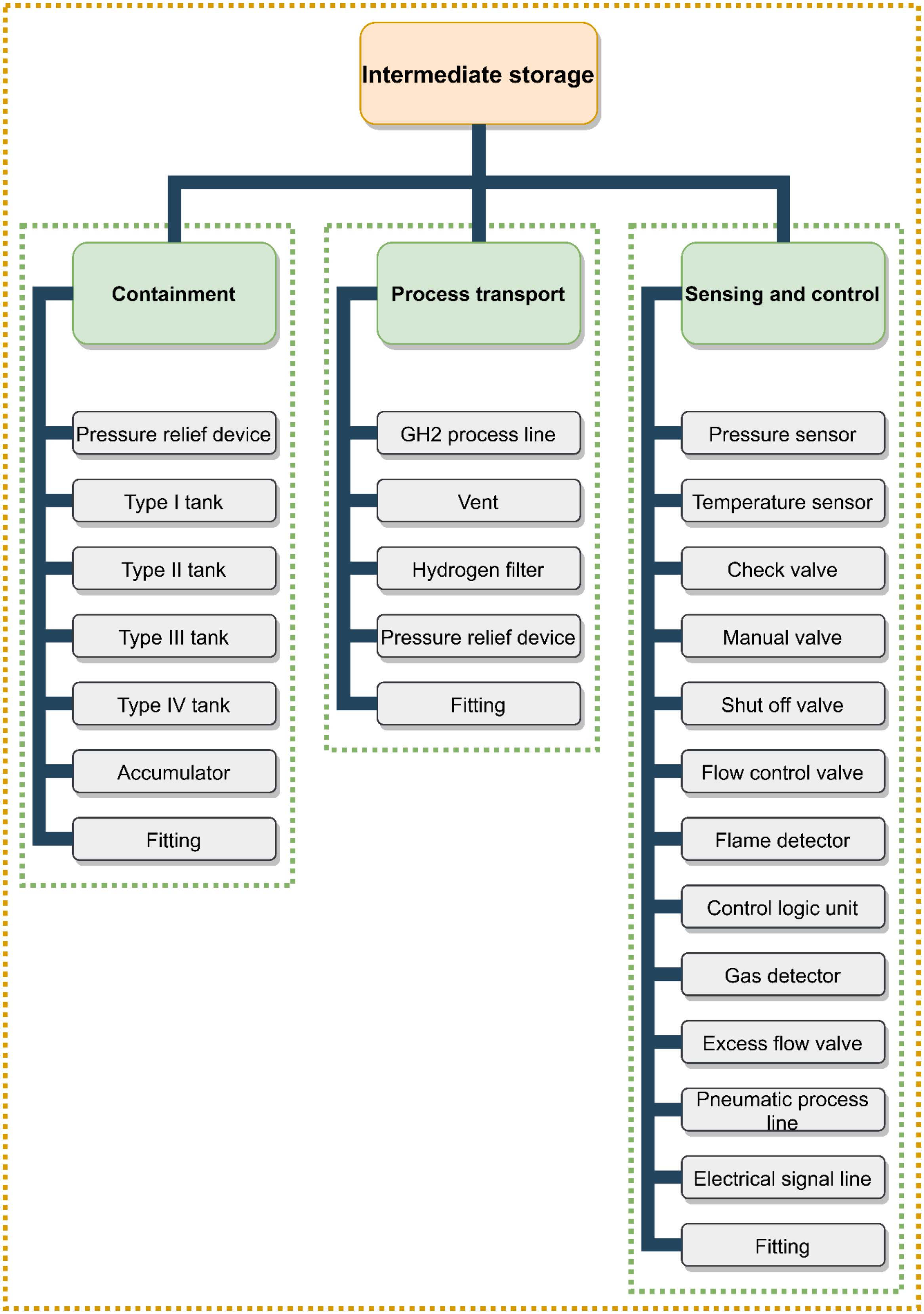


Figure 17- d Generic component hierarchy intermediate storage subsystem

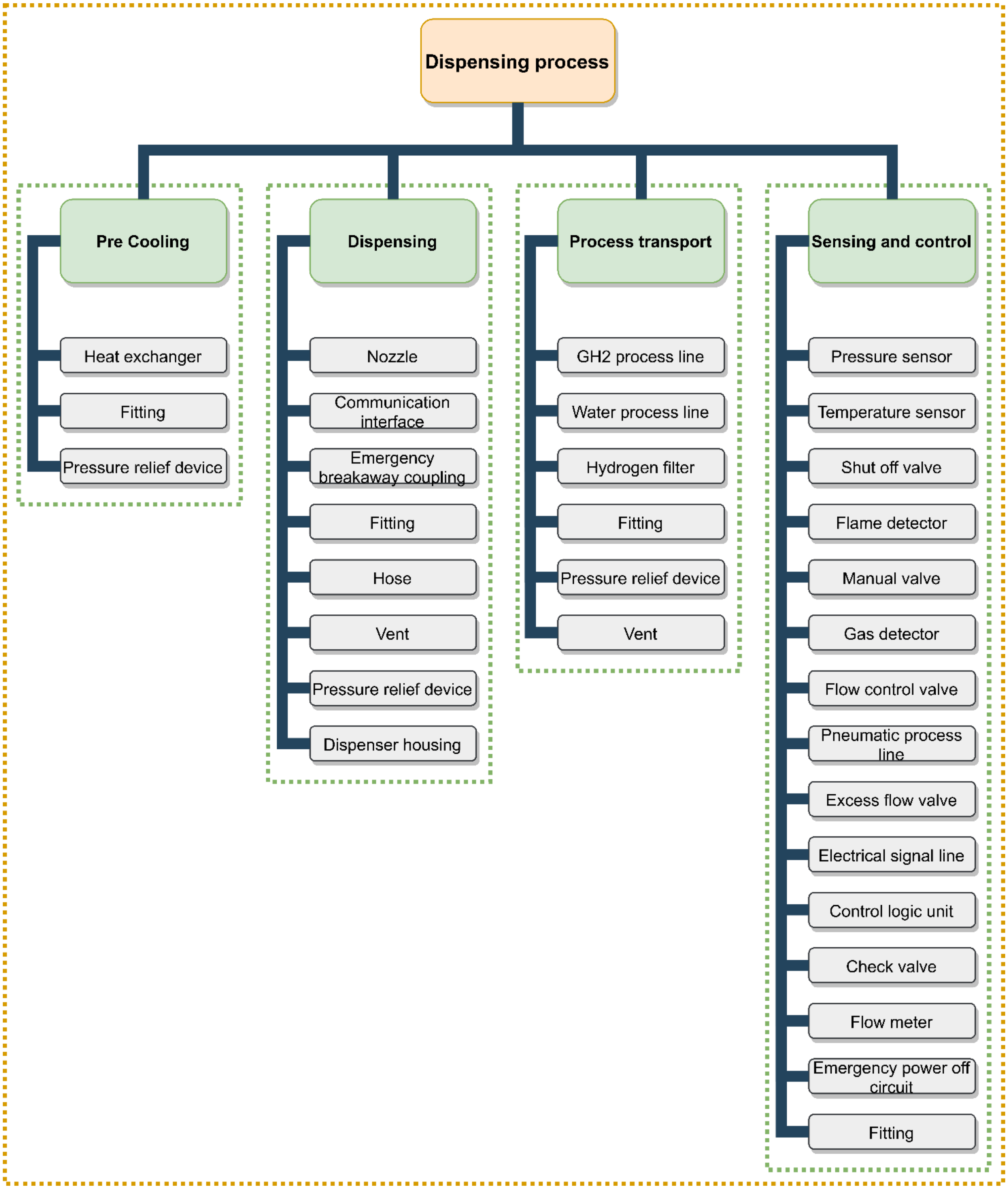


Figure 17- e Generic component hierarchy dispensing subsystem

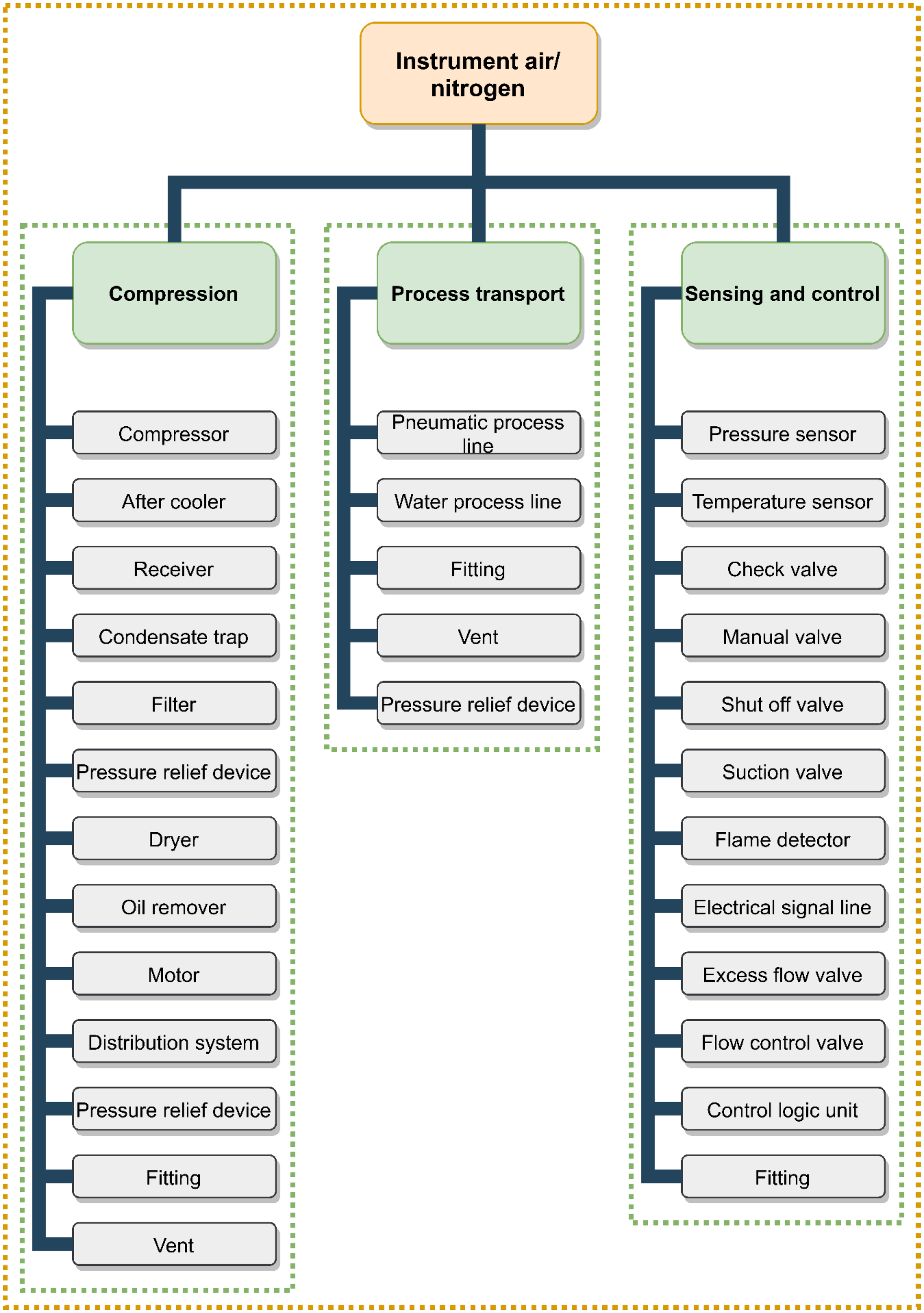


Figure 17- f Generic component hierarchy instrument air/ nitrogen subsystem

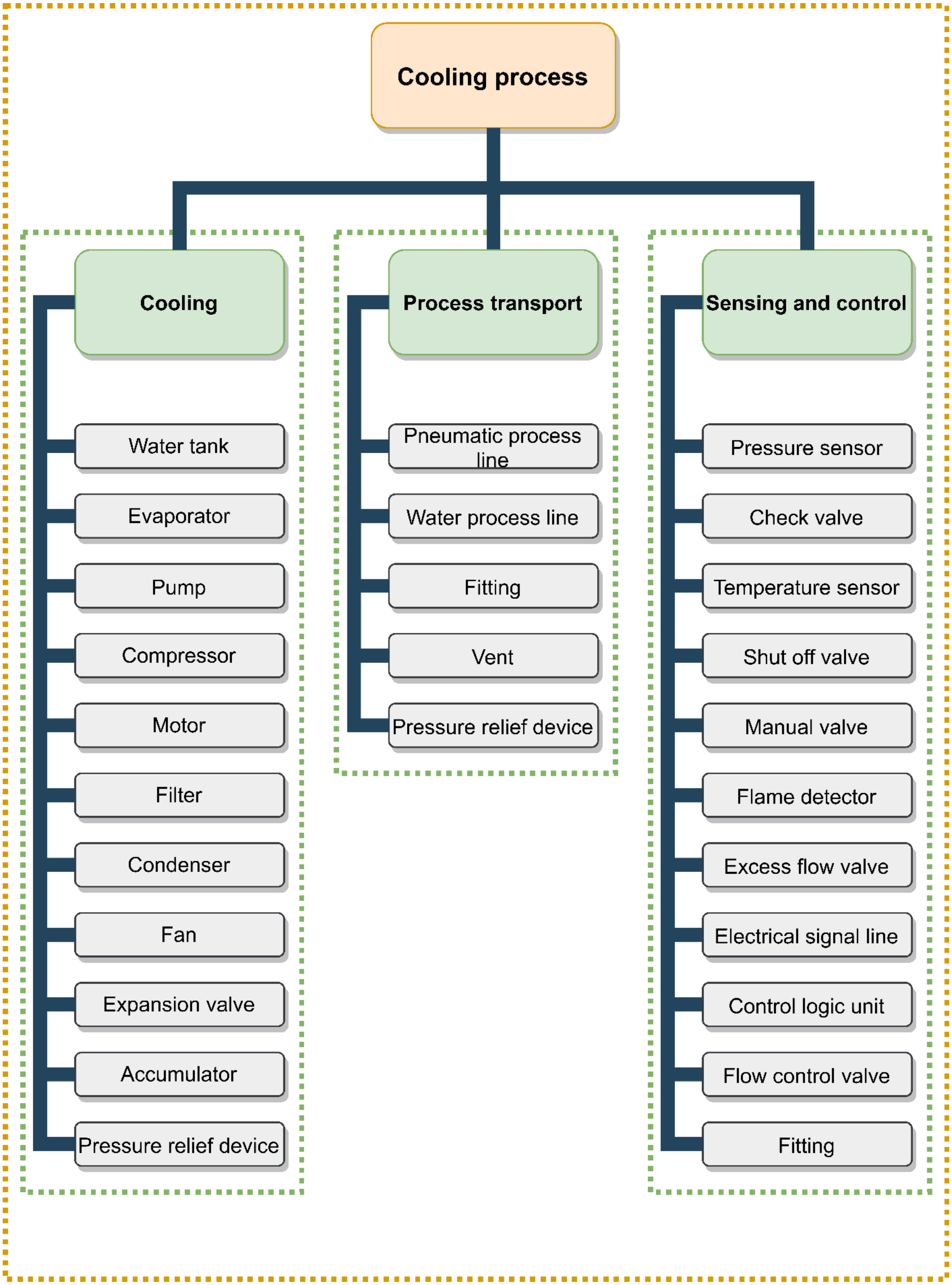


Figure 17- g Generic component hierarchy cooling subsystem

The subsystems are further broken down into functional groups such as transport, sensing and control, and containment among others. These are determined by sorting through all the components within each subsystem for each representative hydrogen fueling station presented in Appendix B. Functional groups and the components within them may be repeated across subsystems. This captures the different use profiles of the components in different subsystems and ensures operating conditions are inherently collected in reliability data.

Finally, the lowest level is made up of components. The components present in this hierarchy come from the components in the representative set of hydrogen fueling stations and any components mentioned in NFPA 2 and ISO 19880-1. This is the level at which component reliability data is typically reported in well-developed databases. The purpose of this is to develop an understanding of component failure for hydrogen fueling stations and use it to inform fault tree analysis. As shown in this hierarchy, some components are very general and will need to be further specified in order to capture meaningful reliability data. However, they will not be included in this hierarchy to keep it concise, as there is too much variation to capture all of the possible component designs in one hierarchy.

Valves are one of the most complicated components to determine an appropriate level of description for, due to the extensive variety of valves that could be included. Ultimately, only the types of valves required in ISO 19880-3, the standard on gaseous hydrogen fueling station valves [83], are included. The valves covered in the standard and included in this hierarchy are check valves, excess flow valves, flow control valves, hose breakaway valves, manual valves, pressure safety valves, and shut-off valves. These cover the array of different valves that may be present across hydrogen fueling stations with the understanding that there is the potential for diversity within each of these valve types. If it is desired to collect data on specific valve designs within each category, that can be added at the component design level 1.1.1.1.1.

Like valves, fittings will also need to be described in further detail in the future of this data collection framework. Fittings are the most common hydrogen release locations so the collection of reliability data for this component is of particular interest [55]. However, fitting styles vary by region and a survey of fittings used will need to be performed to describe fittings at the component design level 1.1.1.1.1. The types of fittings common to hydrogen fueling stations are flanged, welded, and threaded.

This hierarchy is initially validated through discussion with three individual experts from different facets of the hydrogen community each with over ten years of experience in the field. The next step is to validate the hierarchy with industry data to ensure that it includes all the components currently being used in hydrogen fueling stations and that it will be a useable tool for industry data collection.

3.3.2. Failure mode taxonomy

To collect quality reliability data for hydrogen fueling stations there must be a univocal terminology for classification of failures. Standardization of failure mode terminology will allow for the standardization of failure reporting and the ability to aggregate failures across time and stations. Collection of this data will eventually be used to refine failure events and frequencies for fault tree analysis like the example from HyRAM in Figure 18 [30]. This partial fault tree shows all of the failure events that lead to a 100% release at the hydrogen fueling station. Each event in this fault tree has its own frequency and when combined produces a frequency for the top event, in this case 100% release of hydrogen in the system. The overall release probability is used to quantify the ESD node on probability of a hydrogen release like the example from

HyRAM in Figure 4. Failure mode data collection will give researchers a more complete picture of the events that should be included in fault trees and more accurate frequency data. This data will also provide a better understanding of scenarios that evolve from different types of failures, for example release failures vs shutdown failures. A well-defined failure mode taxonomy was developed to fill this knowledge gap.

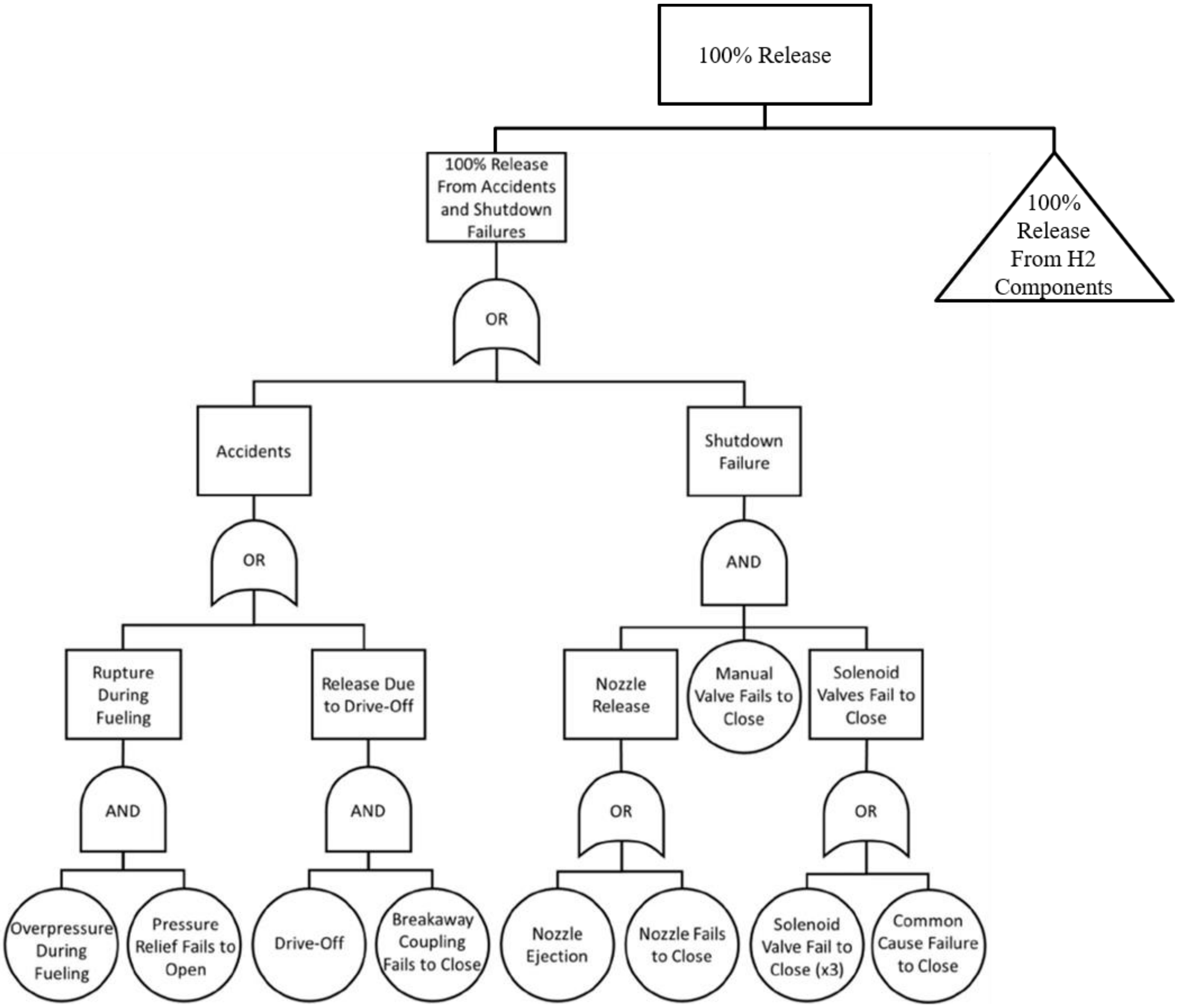


Figure 18 Fault tree for 100% releases from HyRAM [30]

A FMEA like approach is used in combination with hydrogen literature and failure modes from similar industries to develop a failure mode taxonomy. While a traditional FMEA identifies failure modes, effects, detection, compensations, and severity to develop an entire picture of risk, this analysis only identifies failure modes for system components.

3.3.2.1. Method and data: Survey of FMEAs performed on systems similar to hydrogen fueling stations

Several publicly available FMEA and failure mode sources from similar systems and industries are used to aid in the construction of a failure mode taxonomy for hydrogen fueling stations. No publicly available FMEAs performed exclusively on hydrogen fueling stations are available so the search is expanded to similar systems such as hydrogen fuel cell vehicles and adjacent industries such as oil and gas. This limitation makes it even more important for the taxonomy to be validated with industry data.

Failure modes from OREDA are analyzed for their applicability to hydrogen fueling station components [70]. It is determined that some of the failure modes are the same but OREDA includes more than is necessary for hydrogen fueling stations. An FMEA performed by the National Highway Traffic Safety Administration (NHTSA) on hydrogen vehicles includes a succinct list of failure modes that adequately describes failures for the components that were considered, many of which are applicable to hydrogen stations [84]. An FMEA of a hydrogen fueling station performed by the Hydrogen Station Equipment Performance Device (HyStEP) team includes a long list of failure modes, some of which are failure causes rather than failure modes [85]. This source considers failure modes at a subsystem level rather than a component level, however some of the failure modes are still applicable to hydrogen components. An FMEA of a massive gas injection disruption mitigation system is reviewed and has an appropriate number of failure modes that adequately cover all failures for each component [86]. Many of these are applicable to components used in hydrogen fueling stations, and are described at a similar level of detail. A high level FMEA of system failures for a hydrogen fuel cell system reiterates common failure modes but lacks a comprehensive description of component failure modes [87]. An FMEA of a hydrogen enriched natural gas system provides a list of detailed failure modes and mechanisms that is too system specific to be applicable to hydrogen fueling stations [88]. An FMEA of a liquid hydrogen storage system provides a detailed list of failure modes combined with failure causes [89]. These are useful for the consideration of liquid hydrogen specific failure modes but need to be simplified to a more generic taxonomy. The failure modes present in these sources are listed in Table 13 and Table 14.

Table 13 Failure modes from FMEAs similar to hydrogen fueling stations

Source	**OREDA**	**NHTSA**	**HyStEP**	**INL**
Subject of FMEA	**Oil and gas industry**	**Hydrogen fuel cell vehicle**	**Hydrogen station equipment performance device**	**Massive gas injection disruption mitigation system**
Failure modes	Abnormal instrument reading	Become bent/damaged	Backflow	Arc fire
	Abnormal output high	External leak	Contamination	Capacitance change
	Abnormal output low	External rupture	Data processed incorrectly	Contamination
	Breakdown	Fail closed	Exhaust gas in unsafe location	Drift
	Delayed operation	Fail open	Fail open	Erratic operation
	Erratic output	Fail to function properly	Failure of explosion cabinet	Erratic reading
	External leakage of fuel	Fail to vent	File in wrong format	Excessive signal attenuation
	External leakage of process medium	Hole in filter media	Incorrect sensor reading	External leak
	External leakage of utility medium	Internal leak	Incorrect signals	External rupture
	Fail to close on demand	Internal rupture	Loose connection	Fail closed
	Fail to function on demand	Not functional	Loss of containment	Fail off
	Fail to open on demand	Plugged	Loss of signal	Fail on demand
	Fail to regulate	Restrict air flow	Low flow	Fail to regulate pressure
	Fail to start on demand	Restrict coolant flow	No alarm on demand	Fails to operate
	Fail to stop on demand	Restrict fuel flow	No connection	Fails to reclose
	Fail to synchronize	Short circuit	No data collection	Fails to run
	Faulty output frequency	Vent inappropriately	No electronic file	Fails to start
	Faulty output voltage		No flow	Fails to stop
	High output		No power	Internal leak past seat
	Insufficient heat transfer		Not venting	Internal rupture
	Internal leakage		Over pressurization	Leak across diaphragm
	Loss of redundancy		Pressure fail high	Leakage at inlet side
	Low output		Pressure fail low	Leakage at outlet side
	Low output unknown reading		Pressure fail null	Mechanical failure
	Minor in service problems		Reverse flow	Open circuit
	No output		Sensor inputs wrong scale	Overspeed
	Noise		Sensors don’t meet specifications	Plugging
	Operates without demand		Sensors not calibrated	Rupture of compressor body
	Other		Sensors not properly installed	Short circuit
	Overheating		Sensors unsuitable	Spurious operation

Source	**OREDA**	**NHTSA**	**HyStEP**	**INL**
Subject of FMEA	**Oil and gas industry**	**Hydrogen fuel cell vehicle**	**Hydrogen station equipment performance device**	**Massive gas injection disruption mitigation system**
	Parameter deviation		Spontaneous shutdown	Underspeed
	Plugged/chocked		Stuck connection	
	Spurious high-level alarm signal		System doesn’t shut down on demand	
	Spurious low-level alarm signal		System doesn’t shut down at safety thresholds	
	Spurious operation		Temperature fail high	
	Spurious stop		Temperature fail low	
	Structural deficiency		Temperature fail null	
	Unknown		Touch screen unsuitable	
	Valve leakage in closed position		Touch screen inoperable	
	Very low output		Unable to open valve	
	Vibration		Uncontrolled release of gas to atmosphere	
			Wrong connection	

Table 14 Failure modes from FMEAs similar to hydrogen fueling stations

Source	**IEEE**	**AHRI**	**SyRRA Lab**
Subject of FMEA	**Hydrogen fuel cell system**	**Hydrogen enriched natural gas system**	**Liquid hydrogen storage system**
Failure modes	Degradation	Appliance gets a false flame signal	Air supply malfunction
	Fail to cool down	Condensate dripping into burner	Circuit failure due to external accident
	Fail to open	Condensate system cannot withstand hydrochloric acid	Circuit malfunction due to cryogenic temperatures
	Fail to open on demand	Control valves unable to facilitate change in gas flow	Circuit malfunction due to cryogenic temperatures
	Fail to regulate	Cracking burners	Controller fail to commence operation
	Fail to strain properly	Gas accumulation	Controller fail to stop operation
	Fail to supply air	Gas line joints/components leaking gas	Controller failure to stop hydrogen release
	Fail to supply water to fuel cell stack	Higher Nox levels	Controller failure to stop hydrogen release
	Flooding	Increased corrosion in vent	Controller malfunction
	Freezing	Light back of fuel gas	Controller malfunction operation when not needed
	Leakages	Material failure through hydrogen embrittlement	Failure of outer tank wall due to external fire
	Over heating	Melting/failure of seals	Fittings fail due to manufacturing/installation
	Spurious operation	Noise/poor combustion	Leak of hydrogen into vacuum between walls
		Temperature of components exceeds design limits	Leakage
		Vent terminal dripping condensate	Leakage due to material failure
		Vents exceed rated temperature	Leakage from fittings and connecting pipe
		Vents exceed standard limit temperature	Leakage from mechanical failure or installation error
			Leakage from pump due to seal failure or installation error
			Leakage to/from internal piping
			Malfunction due to cryogenic temperatures
			Mechanical failure due to pressure cycling fatigue
			Mechanical failure, unable to close
			Operation failure
			Overpressure from failed pressure safety valve operation
			Pump fail to perform adequately
			Pump fails to deliver H2
			Pump operates prematurely due to controller error
			Puncture of outer tank due to debris or collision
			Rupture due to collision
			Tank rupture due to collision or accident error

Comparing failure modes from different applications is helpful to see the standard language that is used to describe failure modes. A list of common failure modes is created in Table 15 by cross-referencing these sources to see which failure modes are used repeatedly. These sources are all considered in the process of creating a standardized failure mode taxonomy for hydrogen fueling station components.

Table 15 General failure modes applicable to hydrogen fueling stations

General failure modes applicable to hydrogen fueling stations
Bent/warped/damaged
Contamination
Drift
Erratic output
Fail closed
Fail open
Fail to function
Fail to stop
Freezing
Leakage
Noise
Open circuit
Operation failure
Overheating
Overspeed
Plugging
Rupture
Short circuit
Spurious operation
Vibration

3.3.2.2. Result: Development of hydrogen fueling station failure modes

A top-down approach is taken to ensure that any failures that cause overall system failure are captured even if they do not cause component failure. To this end, it is determined that the main function of a hydrogen fueling station is to provide hydrogen within certain process parameters on demand. This system fails by not providing hydrogen on demand, not providing hydrogen within the acceptable process parameters, or not containing hydrogen until there is a demand. Each component is considered individually while looking at the list of generic failure modes applicable to hydrogen fueling station in Table 15. Any failure modes that apply to that component are used from this table. If there are additional ways in which the component could cause one of the three system failures described above, then another failure mode is created to describe this event. These new failure modes are labeled in green in Table 16. Through this process, a taxonomy of failure modes specific to hydrogen fueling components is created. These components have the standard naming convention for failure modes, but are specifically tailored to hydrogen where needed. Definitions for each failure mode have been developed in the context of a hydrogen fueling station and are presented in Table 16. The failure modes and definitions are initially validated through discussion with the three individual experts described before.

The taxonomy of failure modes is presented below in Table 17 through Table 26. Each functional group is presented in a separate table for ease of viewing. These functional groups correspond to the functional groups (green boxes) in the generic component hierarchy Figure 17-a though 17-g.

Table 16 Failure mode taxonomy definitions for hydrogen fueling station components

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
Drift	Erroneous reading of a sensor
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 disconnect	Components meant to disconnect does not do so on demand
Fail to evaporate	Hydrogen remains in liquid form after passing through evaporator
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
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
Overspeed	Component operates above desired/specified speed
Plugging	Buildup of material restricting flow
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)
Stuck connection	Component is stuck at point of contact (e.g. nozzle)
Underspeed	Component operates below desired/specified speed

Failure modes labeled in green have been specifically developed for hydrogen fueling stations

Table 17 Failure mode taxonomy containment functional group

Functional group	Containment						
Component	Double walled tank	Type 1 tank	Type 2 tank	Type 3 tank	Type 4 tank	Pressure relief device	Fitting
Failure modes	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen
	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen
	Internal leak hydrogen					Fail to close	
	Internal rupture hydrogen					Fail to operate	
						Spurious operation	

Table 18 Failure mode taxonomy evaporation functional group

Functional group	Evaporation	
Component	Ambient air evaporator	Pressure relief device
Failure modes	External leak hydrogen	External leak hydrogen
	External rupture hydrogen	External rupture hydrogen
	Fail to evaporate	Fail to close
	Plugging	Fail to operate
		Spurious operation

Table 19 Failure mode taxonomy pre-cooling functional group

Functional group	Pre-cooling		
Component	Heat exchanger	Fitting	Pressure relief device
Failure modes	External leak hydrogen	External leak hydrogen	External leak hydrogen
	External leak utility medium	External rupture hydrogen	External rupture hydrogen
	External rupture hydrogen		Fail to close
	External rupture utility medium		Fail to operate
	Insufficient heat transfer		Spurious operation
	Plugging		

Table 20 Failure mode taxonomy process transport and piping functional group

Functional group	Process transport and piping									
Component	LH2 Process Line	GH2 Process line	Cryogenic liquid pump	Fitting	Flexible unloading hose	Manifold	Hydrogen filter	Vent	Pressure relief device	Water process line
Failure modes	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen	Contamination	Plugging	External leak hydrogen	External leak utility medium
	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	Plugging		External rupture hydrogen	External rupture utility medium
	Plugging	Plugging	Fail to operate		Plugging	Plugging			Fail to close	Plugging
			Fail to stop						Fail to operate	
			Internal leak hydrogen						Spurious operation	
			Internal rupture hydrogen							
			Noise							
			Overheating							
			Overspeed							
			Plugging							
			Spurious operation							
			Spurious stop							
			Underspeed							
			Vibration							

Table 21 Failure mode taxonomy compression functional group

Functional group	Compression								
Component	Motor	Coolant filter	Gearbox	Pressure relief device	Compressor	Booster	Heat exchanger	Fitting	Vent
Failure modes	Fail to operate	Contamination	Fail to operate	External leak hydrogen	Contamination	External leak hydrogen	External leak hydrogen	External leak hydrogen	Plugging
	Fail to stop	Plugging	Noise	External rupture hydrogen	External leak hydrogen	External rupture hydrogen	External leak utility medium	External rupture hydrogen	
	Noise		Overheating	Fail to close	External leak utility medium	Fail to operate	External rupture hydrogen		
	Overheating		Vibration	Fail to operate	External rupture hydrogen	Fail to stop	External rupture utility medium		
	Overspeed			Spurious operation	External rupture utility medium	Internal leak hydrogen	Insufficient heat transfer		
	Spurious operation				Fail to operate	Internal rupture hydrogen	Plugging		
	Spurious stop				Fail to stop	Overspeed			
	Underspeed				Internal leak hydrogen	Plugging			
	Vibration				Internal rupture hydrogen	Spurious operation			
					Noise	Spurious stop			
					Overheating	Underspeed			
					Overspeed	Vibration			
					Spurious operation				
					Spurious stop				
					Underspeed				
					Vibration				

Table 22 Failure mode taxonomy dispensing functional group

Functional group	Dispensing							
Component	Nozzle	Communication interface	Emergency breakaway coupling	Fitting	Hose	Vent	Pressure relief device	Dispenser housing
Failure modes	Bent warped damaged	Bent warped damaged	External leak hydrogen	External leak hydrogen	External leak hydrogen	Plugging	External leak hydrogen	Bent warped damaged
	External leak hydrogen	Erratic output	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen		External rupture hydrogen	
	External rupture hydrogen	Fail to operate	Fail open		Plugging		Fail to close	
	Fail closed		Fail to disconnect		Stuck connection		Fail to operate	
	Fail open						Spurious operation	
	Fail to operate							
	Fail to stop							
	Operation error							
	Plugging							
	Spurious operation							
	Stuck connection							

Table 23 Failure mode taxonomy sensing and control functional group

Functional group	Sensing and control							
Component	Pressure sensor	Flow control valve	Temperature sensor	Check valve	Pneumatic process line	Manual valve	Shut-off valve	Electrical signal line
Failure modes	Abnormal output-high	External leak hydrogen	Abnormal output-high	External leak hydrogen	External leak utility medium	External leak hydrogen	External leak hydrogen	Open circuit
	Abnormal output-low	External rupture hydrogen	Abnormal output-low	External rupture hydrogen	External rupture utility medium	External rupture hydrogen	External rupture hydrogen	Short circuit
	Drift	Fail closed	Drift	Fail close	Plugging	Fail close	Fail closed	
	Erratic output	Fail open	Erratic output	Fail open		Fail open	Fail open	
	External leak hydrogen	Fail to operate	External leak hydrogen	Internal leak hydrogen		Internal leak hydrogen	Fail to operate	
	External rupture hydrogen	Internal leak hydrogen	External rupture hydrogen	Internal rupture hydrogen		Internal rupture hydrogen	Internal leak hydrogen	
	Fail to operate	Internal rupture hydrogen	Fail to operate	Plugging		Plugging	Internal rupture hydrogen	
		Plugging		Restrict flow		Restrict flow	Plugging	
		Restrict flow					Restrict flow	
		Spurious operation					Spurious operation	

Table 24 Failure mode taxonomy sensing and control functional group continued

Functional group	Sensing and control						
Component	Excess flow valve	Flame detector	Control logic unit	Gas detector	Fitting	Flow meter	Emergency power off circuit
Failure modes	External leak hydrogen	Abnormal output-high	Abnormal output-high	Abnormal output-high	External leak hydrogen	Drift	Open circuit
	External rupture hydrogen	Abnormal output-low	Abnormal output-low	Abnormal output-low	External rupture hydrogen	Erratic output	Short circuit
	Fail close	Drift	Erratic output	Drift		Fail to operate	
	Fail open	Erratic output	Fail to operate	Erratic output			
	Internal leak hydrogen	Fail to operate	Spurious operation	Fail to operate			
	Internal rupture hydrogen						
	Plugging						
	Restrict flow						

Table 25 Failure mode taxonomy air/ nitrogen compression functional group

Functional group	Air/ nitrogen compression								
Component	Compressor	After cooler	Receiver	Condensate trap	Filter	Pressure relief device	Fitting	Vent	Suction valve
Failure modes	Contamination	External leak utility medium	External leak utility medium	Contamination	Contamination	External leak utility medium	External leak utility medium	Plugging	External leak utility medium
	External leak utility medium	External rupture utility medium	External rupture utility medium	External leak utility medium	Plugging	External rupture utility medium	External rupture utility medium		External rupture utility medium
	External rupture utility medium	Insufficient heat transfer		External rupture utility medium		Fail to close			Fail closed
	Fail to operate	Plugging		Plugging		Fail to operate			Fail open
	Fail to stop					Spurious operation			Fail to operate
	Internal leak utility medium								Internal leak utility medium
	Internal rupture utility medium								Internal rupture utility medium
	Noise								Plugging
	Overheating								Restrict flow
	Overspeed								Spurious operation
	Spurious operation								
	Spurious stop								
	Underspeed								
	Vibration								

Table 26 Failure mode taxonomy cooling functional group

Functional group	Cooling										
Component	Water tank	Evaporator	Pump	Compressor	Motor	Filter	Condenser	Fan	Expansion valve	Accumulator	Pressure relief device
Failure modes	External leak utility medium	External leak utility medium	External leak utility medium	Contamination	Fail to operate	Contamination	External leak utility medium	Fail to operate	External leak utility medium	External leak utility medium	External leak utility medium
	External rupture utility medium	External rupture utility medium	External rupture utility medium	External leak utility medium	Fail to stop	Plugging	External rupture utility medium	Fail to stop	External rupture utility medium	External rupture utility medium	External rupture utility medium
		Insufficient heat transfer	Fail to operate	External rupture utility medium	Noise		Insufficient heat transfer	Noise	Fail close	Fail closed	Fail to close
		Plugging	Fail to stop	Fail to operate	Overheating		Plugging	Overspeed	Fail open	Fail open	Fail to operate
			Internal leak utility medium	Fail to stop	Overspeed			Spurious operation	Internal leak utility medium	Internal leak utility medium	Spurious operation
			Internal rupture utility medium	Internal leak utility medium	Spurious operation			Spurious stop	Internal rupture utility medium	Internal rupture utility medium	
			Noise	Internal rupture utility medium	Spurious stop			Underspeed	Plugging		
			Overheating	Noise	Underspeed			Vibration	Restrict flow		
			Overspeed	Overheating	Vibration						
			Plugging	Overspeed							
			Spurious operation	Spurious operation							
			Spurious stop	Spurious stop							
			Underspeed	Underspeed							
			Vibration	Vibration							

Chapter 3 described the methods, data, and results needed to create a reliability data collection framework for hydrogen fueling stations. The work reviewed hydrogen QRA data types identified by Moradi and Groth (2019) [5]. System data including configuration and component counts as well as frequency data including release, ignition, and mitigation occurrence were found to be the most underdeveloped data types that are needed to support hydrogen QRA. The data collection framework developed in this thesis seeks to enable the collection of system and frequency data. Current hydrogen safety data collection tools were analyzed to determine their accuracy and usability in QRA. This analysis found major gaps in collection of failure modes, failure mechanisms, system response, hydrogen accumulation, hydrogen detection, and component life (e.g. age, operating hours, demands). A review of reliability data collection best practice showed the importance of component hierarchy, failure mode data collection, failure mechanism data collection, and thorough process documentation. Lessons learned from current hydrogen safety data collection and best practices were used to develop 23 requirements for a hydrogen reliability data collection framework. These requirements include the characteristics of the data collection tool as well as the static, failure, and maintenance data that will need to be collected.

A generic hydrogen component hierarchy was then developed based on 6 published, representative hydrogen fueling station designs. These systems were decomposed with a blend of functional and service-based decomposition methods in order to capture the function of each component within the system as well as an exhaustive list of components that may require maintenance and their exact location within the system. A well-defined failure mode taxonomy was developed to accompany the hydrogen fueling station component hierarchy. Commonly used failure modes from similar FMEAs were collected and reviewed for their applicability to hydrogen components. Some of these failure modes were used and new hydrogen-specific failure modes were created to make a failure mode taxonomy. Each failure mode was then defined in the context of a hydrogen fueling station. Together, the requirements, component hierarchy, and failure mode taxonomy create a hydrogen reliability data collection framework that can be used to support QRA.

Chapter 4. Conclusion

4.1. Summary & Technical contributions

4.1.1. Summary

Rigorous QRA and scientifically backed SCS are necessary to enable wider, safer deployment of hydrogen infrastructure. However, QRA needs reliability data, and currently the available hydrogen safety databases are not in a format conducive for use in QRA. This thesis explored what QRA and reliability data currently look like in the context of hydrogen systems and presented a new reliability data collection framework for hydrogen systems that overcomes existing gaps.

The first part of this thesis contains a gap study on literature related to hydrogen QRA to determine the most pressing research needs for enhancing QRA. Lack of hydrogen specific reliability data was the most frequently referenced knowledge gap. This gap motivated this thesis to fill a knowledge gap surrounding hydrogen reliability data, specifically the development of a data collection framework for hydrogen fueling stations. This study consisted of three tasks: reviewing current hydrogen safety and reliability data, developing requirements for a hydrogen reliability data collection framework, and generating a generic component hierarchy and failure mode taxonomy.

Task 1 reviewed hydrogen reliability data types, needs, current data collection tools, and data collection best practices. Hydrogen QRA data needs were reviewed and their current availability and quality examined. It was determined that system and frequency data, identified in Moradi and Groth [5], were the most underdeveloped data types, yet required in order to produce failure, detection, and isolation probabilities for use in QRA. These were chosen as the focus of the data collection framework developed in this thesis.

Four current hydrogen reliability data collection tools were then reviewed for their quality and applicability to QRA: H2Tools Lessons Learned, HIAD, NREL's CDPs, and CHS's failure rate data submission form. It was determined that the data collected by H2Tools was primarily qualitative descriptions of failure events making it a safety database with the ability to determine narratives and lessons learned. HIAD has the potential to collect qualitative and quantitative data about failure events, however voluntary reporting results in mostly qualitative reporting and incomplete data which like H2Tools can only be used to develop narratives and lessons learned. NREL's CDPs are a good starting point for collecting system-level data but fail to adequately define and collect failure modes and mechanisms. The CHS failure rate data submission form collects component level information for a limited number of components. These can be used to determine component failure rates but it lacks data on component life and failure modes and mechanisms. While safety databases are used to inform safety culture, planning, procedures, and best practices, a hydrogen reliability database is needed to inform rigorous QRA.

OREDA was chosen as a model reliability database for best practices as it is well-developed, and the oil and gas industry is analogous to the hydrogen industry. The review of OREDA informed data field requirements to collect high quality reliability data that can be turned into meaningful failure rates. This review also pointed to a need for the development of a generic component hierarchy and well-defined failure mode taxonomy.

In Task 2, hydrogen QRA data needs, gaps in current data collection tools, and reliability data collection best practices were synthesized to develop 23 requirements for a hydrogen reliability data collection framework. These requirements describe three main areas: database characteristics, system and component static data, and event data (failure and maintenance). The full details and justification for these requirements are described in Section 3.2.

The goal of Task 3 was to develop a reliability data collection framework for hydrogen fueling stations by generating a generic component hierarchy and corresponding failure mode taxonomy. These will serve as the backbone to a framework that is complete with data collection requirement from Task 2. A representative set of publicly available hydrogen fueling station designs were analyzed and decomposed to develop the component hierarchy. The components from these stations were sorted and used to build a hierarchy based on a blend of functional and service-based decomposition. The uniqueness of hydrogen fueling station designs merits this change from standard system decompositions. The benefits of this blended decomposition are its intuitiveness and ability to support risk assessment. Non-expert end users are able to easily find components relevant to their needs because of the functional aspect while the exhaustive list of components is a feature of the service-based decomposition. This hierarchy will enable understanding of component failure in the context of system function and operating condition. With this data the hydrogen industry will be able to perform process-based risk assessment with full understanding of system behavior and interactions between system functions and system response as a whole. The generic component hierarchy for hydrogen fueling stations that was developed from this decomposition is presented in Figures 15 a-g and as a larger version in Appendix C.

The well-defined failure mode taxonomy of hydrogen components was developed to correspond to the generic component hierarchy described above and is presented in Tables 16 - 25. The definitions for all the failure modes included in this hierarchy are in Table 16. The failure modes were developed by reviewing publicly available FMEAs related to hydrogen systems and other similar systems due to a lack of FMEA on hydrogen fueling stations. Generic failure modes relevant to hydrogen systems were extracted from these FMEA. Relevant failure modes from this list were applied to each component in the hierarchy and any missing failure modes were developed using an FMEA like approach.

4.1.2. Technical contributions

The work produced by this thesis, summarized above, resulted in three technical contributions to the hydrogen industry:

1. The development of a list of 23 requirements for hydrogen fueling station data collection. The requirements were created through analysis of hydrogen QRA data needs, collection tools, and reliability data collection best practices. There are currently no hydrogen safety data collection tools that adequately capture reliability data from industry, despite the lack of data being the most pressing issue described in hydrogen literature. The requirements developed in this thesis fill the knowledge gap on what a hydrogen reliability data collection framework should look like. They are the first step in building a hydrogen reliability data collection tool to inform rigorous QRA.
2. The creation of a generic component hierarchy for hydrogen fueling stations to support and improve system reliability data collection. Previously, there have been a very limited number of publicly available sources summarizing hydrogen fueling station components. This generic component hierarchy is a technical contribution that presents all the components necessary in hydrogen fueling stations and can be used as

a tool to inform station design, risk assessment, and the development of a hydrogen reliability data collection tool.

3. A well-defined hydrogen component failure mode taxonomy that corresponds to the generic component hierarchy was characterized. Previously, there have been no publicly available sources of hydrogen fueling station component failure modes (HyStEP is at the system function level, all other FMEA discussed in journal articles do not provide the full technical report). In all the FMEA surveyed, none provided definitions of the failure modes used. The definitions developed in this thesis will improve the verifiability, reproducibility, and comparability of future hydrogen fueling reliability data collection and associated risk assessment.

4.2. Recommendations & future work

There is still much work to be done following this project to collect quality hydrogen reliability data that is useable in QRA. This section presents the recommendations and future work to expand the scope of this project and continue the development of a data collection tool the hydrogen industry needs.

The next immediate step will be to present this work to NFPA, ISO, CHS, and other industry organizations to get feedback and promote validation within the hydrogen community. This will provide an opportunity to validate the project with system-specific analysis and ensure that necessary hydrogen reliability data is collected in a way that serves industry needs and paves the way for broader use. Based on this validation, the hierarchy may require the development of additional levels of abstraction (component design and maintainable items) to collect data on more specific components. This will be particularly important for valves and fittings. There is a lot of diversity in types of valves used and QRA would benefit from having failure and operation data specific to valve design. Fittings are the most common hydrogen release location therefore; detailed reliability data collection is necessary to inform better design and targeted risk mitigation. Validation will also be used to ensure all realistic hydrogen fueling station failure modes are characterized. This validation is crucial to the future development of a useable hydrogen fueling station reliability database.

To expand the scope of this project beyond hydrogen storage and fueling, future researchers should expand the framework to include data related to onsite hydrogen production and fuel cell systems for vehicles and backup power. Onsite electrolysis methods include natural gas reforming and water electrolysis, which are being considered for hydrogen fueling stations. Inclusion of fuel cell data would cover failures of fuel cell vehicles and backup power, in the hands of consumers. These will expand the scope of data collection but keep it focused on consumer facing systems rather than large scale production for example.

Future work should include the development of failure mechanisms for the hydrogen fueling station components. This is necessary to understand the underlying cause of failure modes. External factors and human factors should be considered in this phase and accounted for in the developed failure mechanisms. Currently, external factors and human factors are only intrinsically included in the failure mode taxonomy. The future consideration of external factors and human factors will help fill the knowledge gaps identified in Sections 2.3.2 and 2.3.3.

Exploring the physics of failure of these components in another way to fill data gaps for hydrogen reliability data without having failure event data. This means using degradation algorithms to describe how failure mechanisms evolve over time and eventually cause failure. For example, failure mechanisms could be used to see how hydrogen embrittlement will cause failure in hydrogen system components. This is an especially important tool for failures that do not happen often and may not be collected by a reliability data collection tool in the near future. Physics of failure should be used alongside hydrogen system reliability data collection to predict the characteristics of component failures.

Once the framework is adequately validated, UMD should begin collaborative work with NREL, CGA, and CHS to incorporate data requirements, hierarchy, and failure mode taxonomy into their data structures. These organizations already have relationships with US-based hydrogen stations and have the ability to collect timely and comprehensive hydrogen reliability data. This data will be turned into probabilities and frequencies such as component failure, detection, and isolation rates that the industry desperately needs. The ultimate goal is to use the hydrogen reliability data collected to inform rigorous QRA and create a defensible, scientific basis for requirements in ISO19880-1 and NFPA 2 and hydrogen safety as a field.

Appendices

A.1. H2First 300kg/day gaseous delivery station [74]

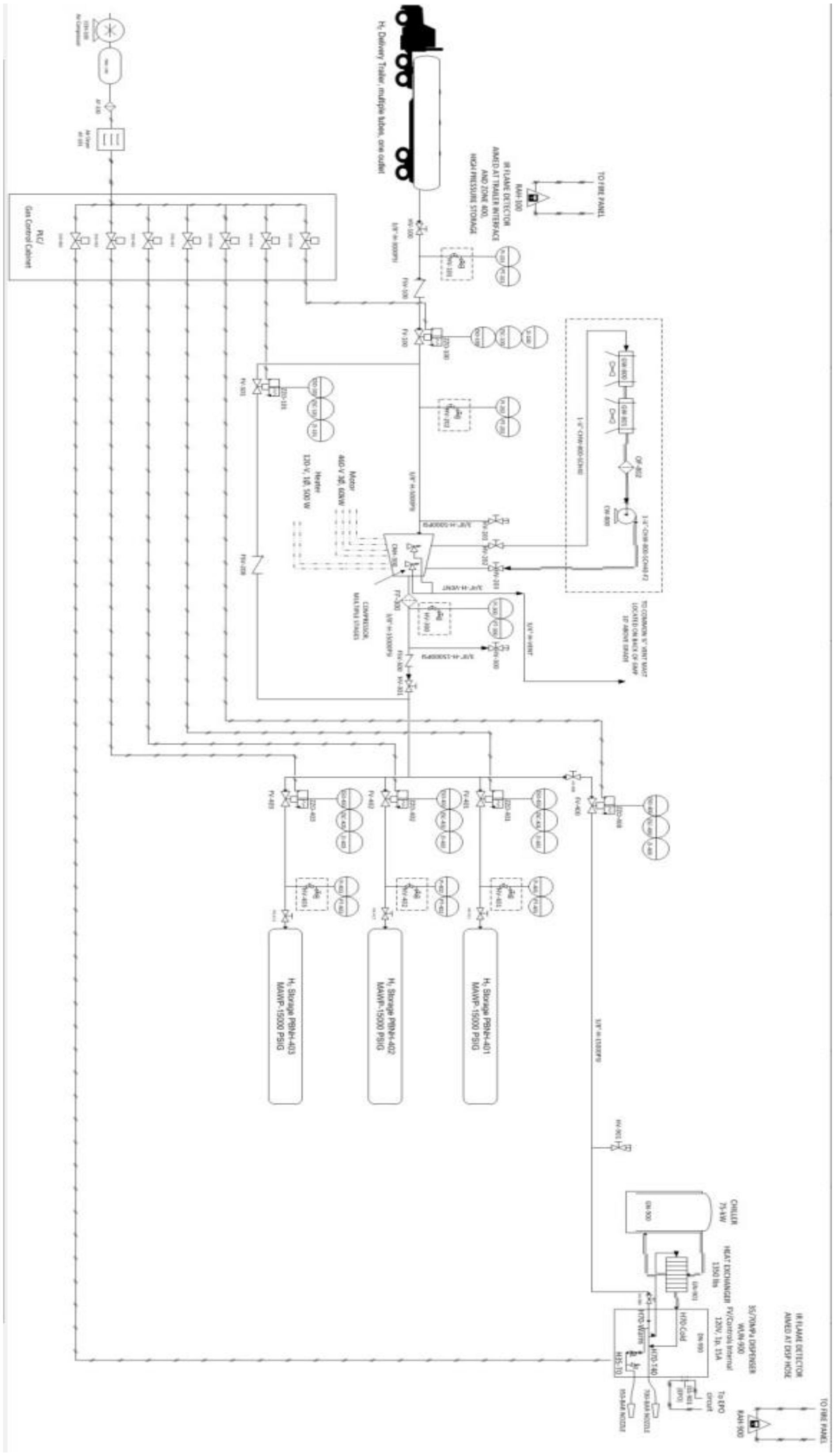


Figure A-1 Reference station P&ID 300 kg/day gaseous delivery [74]

A.2. H2First 300kg/day liquid delivery station [74]

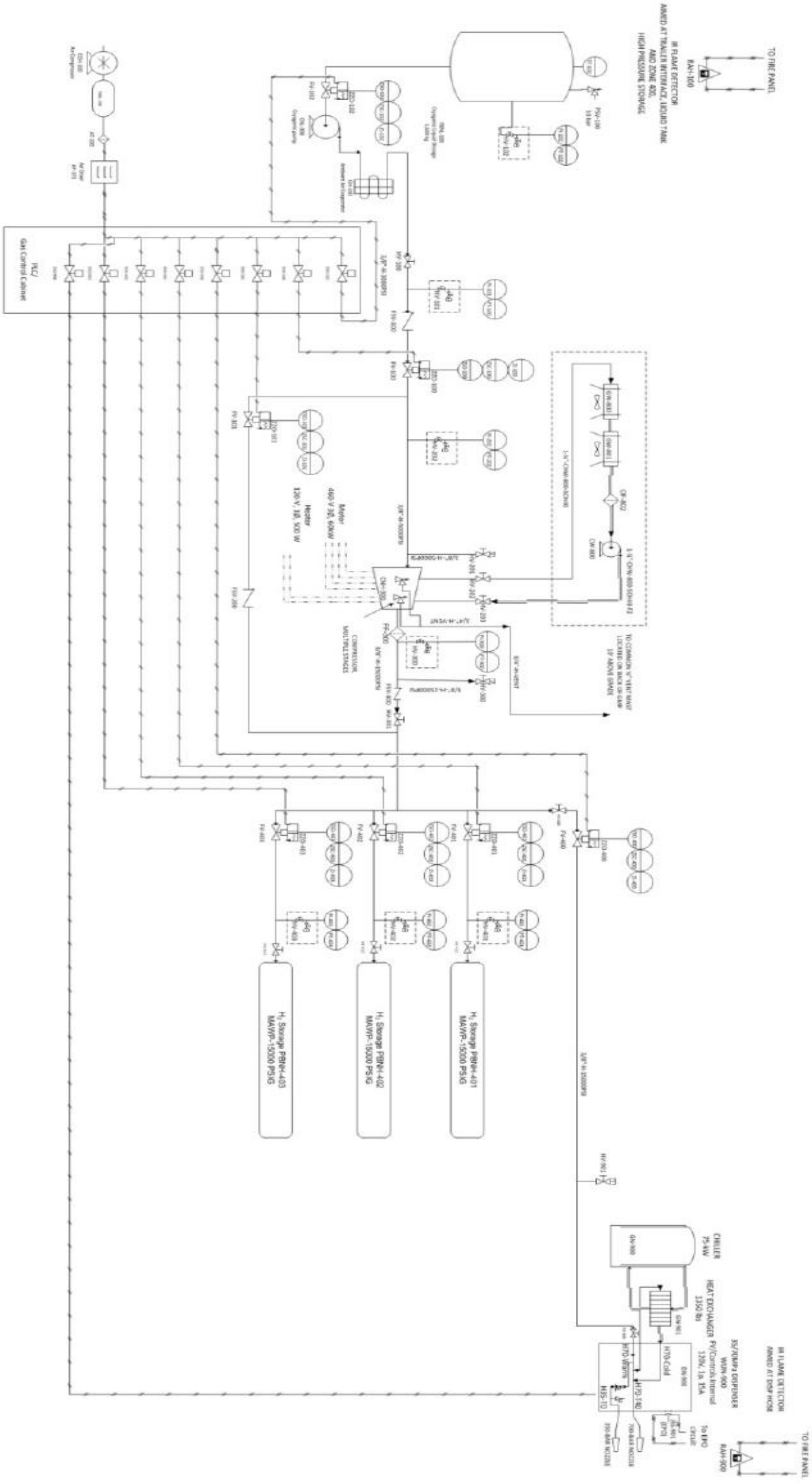


Figure A-2 Reference station P&ID 300 kg/day liquid delivery [74]

A.3. H2First 600kg/day gaseous delivery station [75]

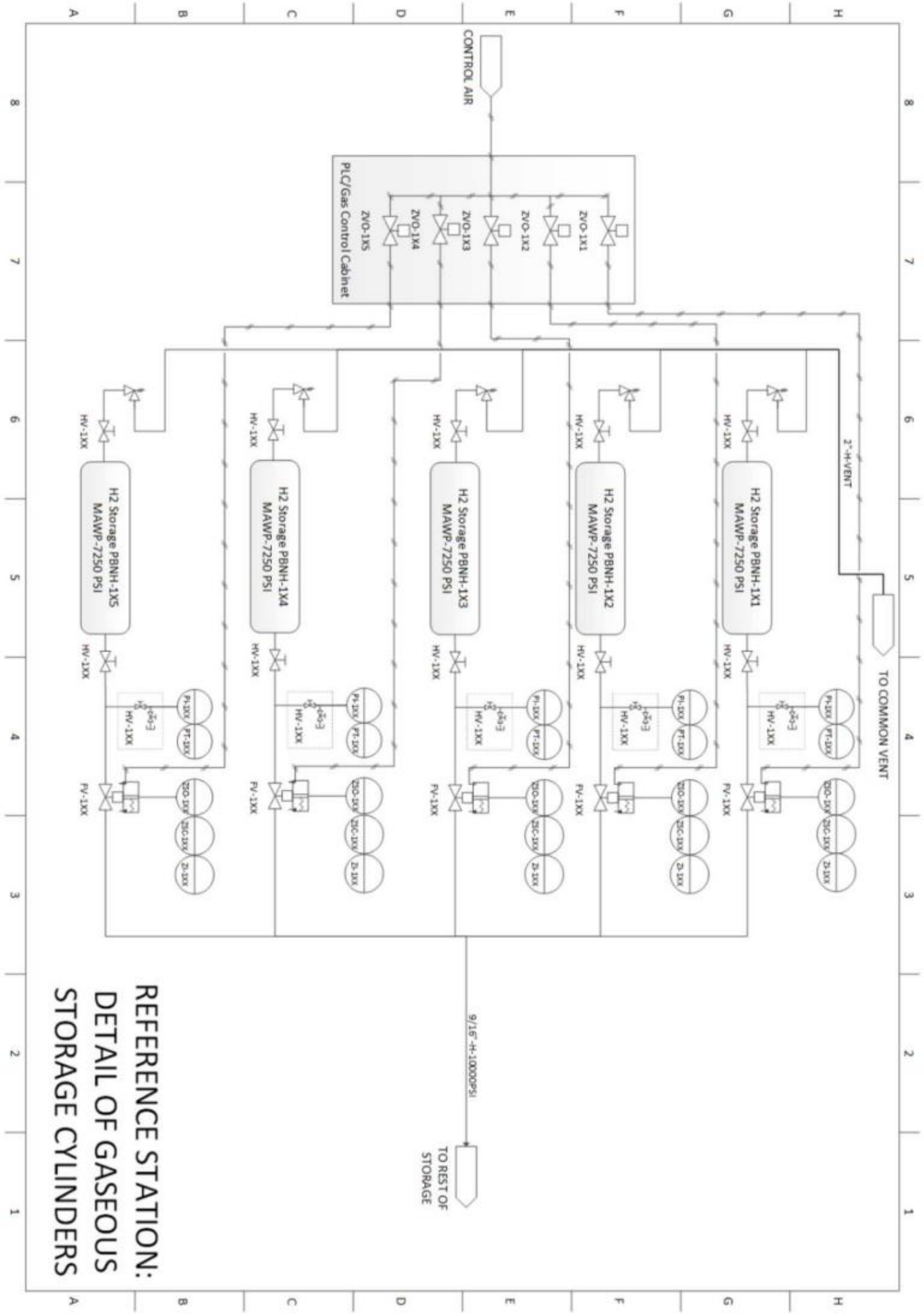
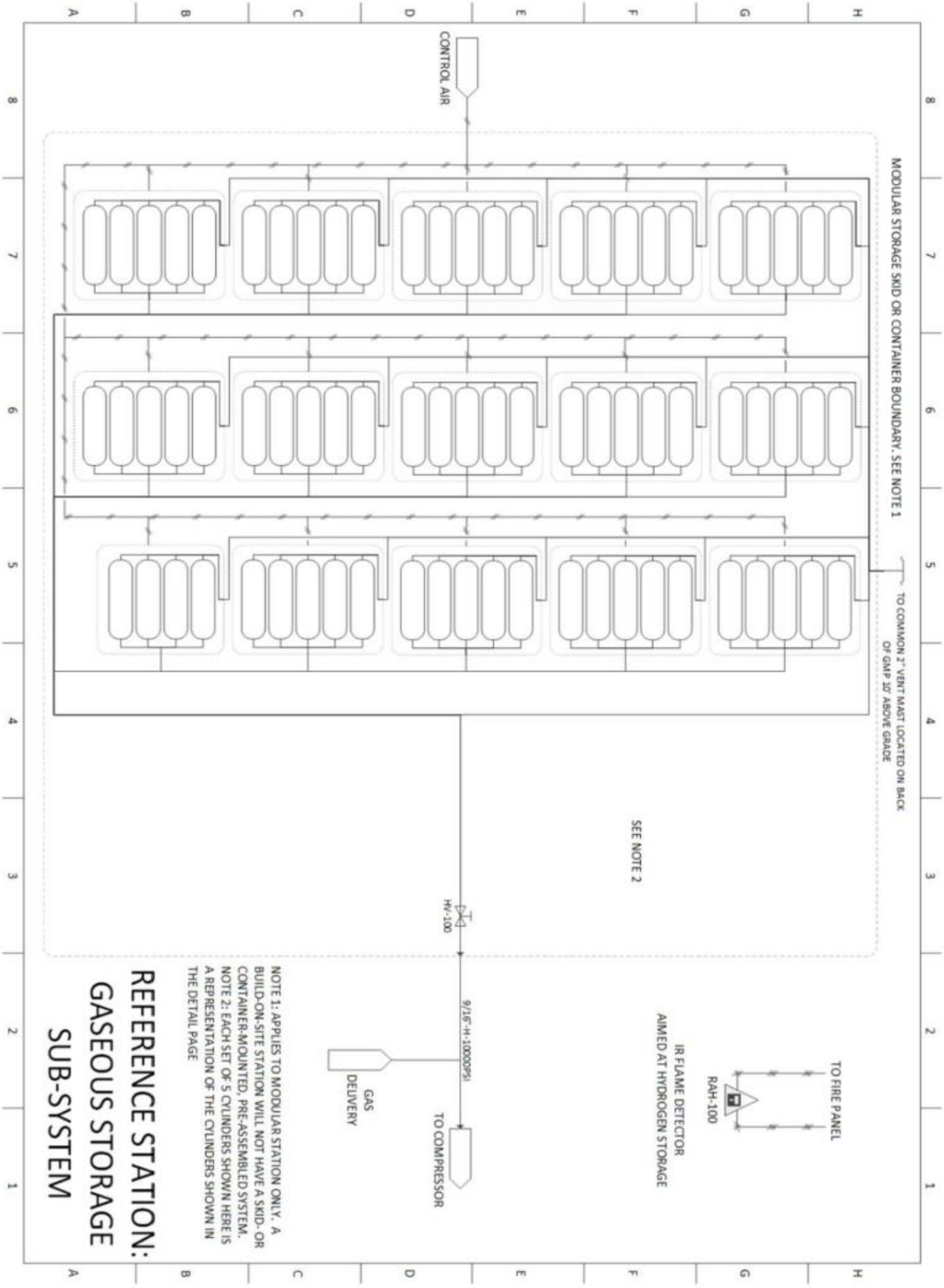


Figure A-3 Reference station P&ID 600 kg/day gaseous delivery storage cylinders [75]



NOTE 1: APPLIES TO MODULAR STATION ONLY. A BUILD-ON-SITE STATION WILL NOT HAVE A SKID- OR CONTAINER-MOUNTED, PRE-ASSEMBLED SYSTEM.
NOTE 2: EACH SET OF 5 CYLINDERS SHOWN HERE IS A REPRESENTATION OF THE CYLINDERS SHOWN IN THE DETAIL PAGE

Figure A-4 Reference station P&ID 600 kg/day gaseous delivery storage subsystem [75]

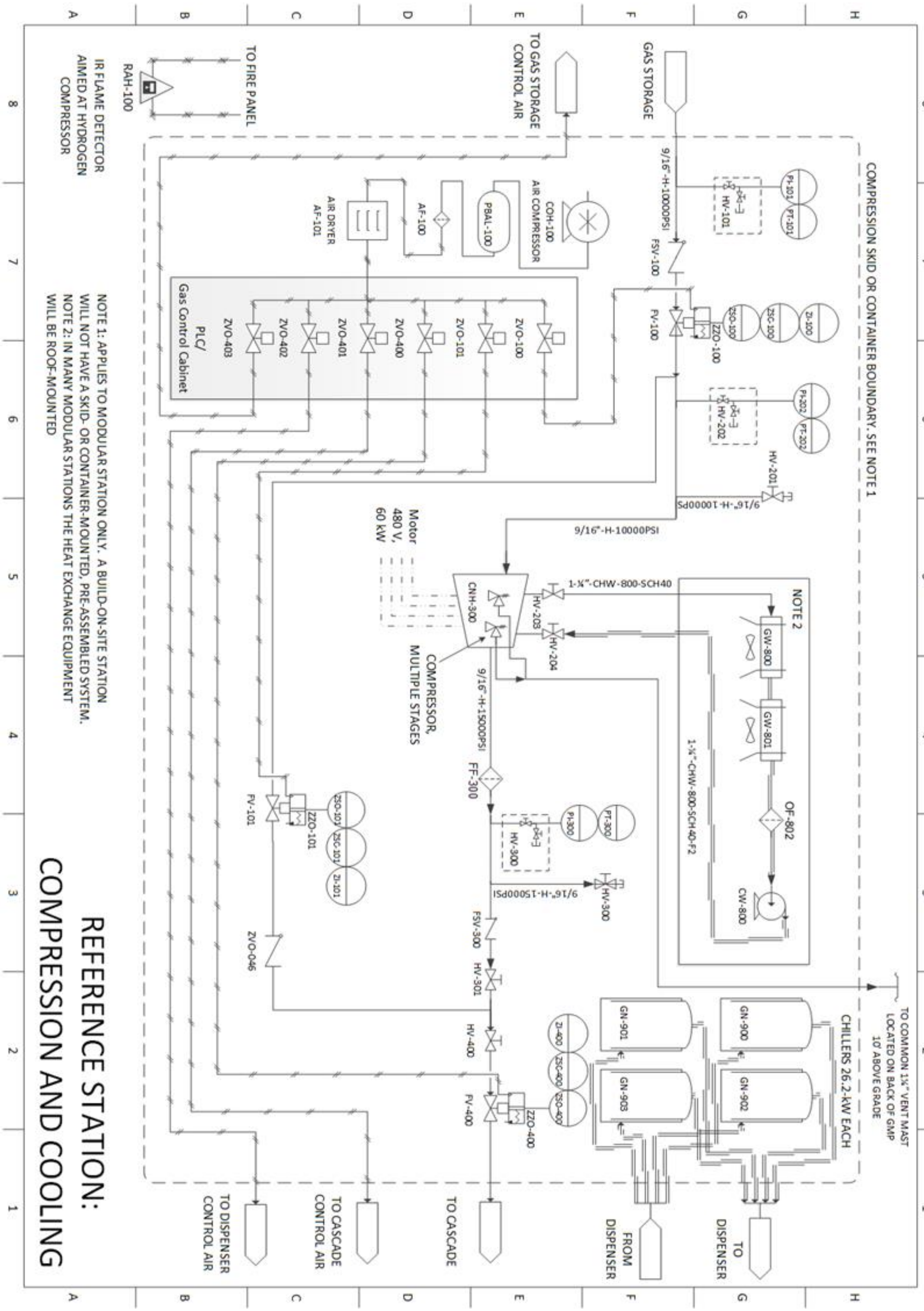


Figure A-5 Reference station P&ID 600 kg/day compression and cooling subsystem[75]

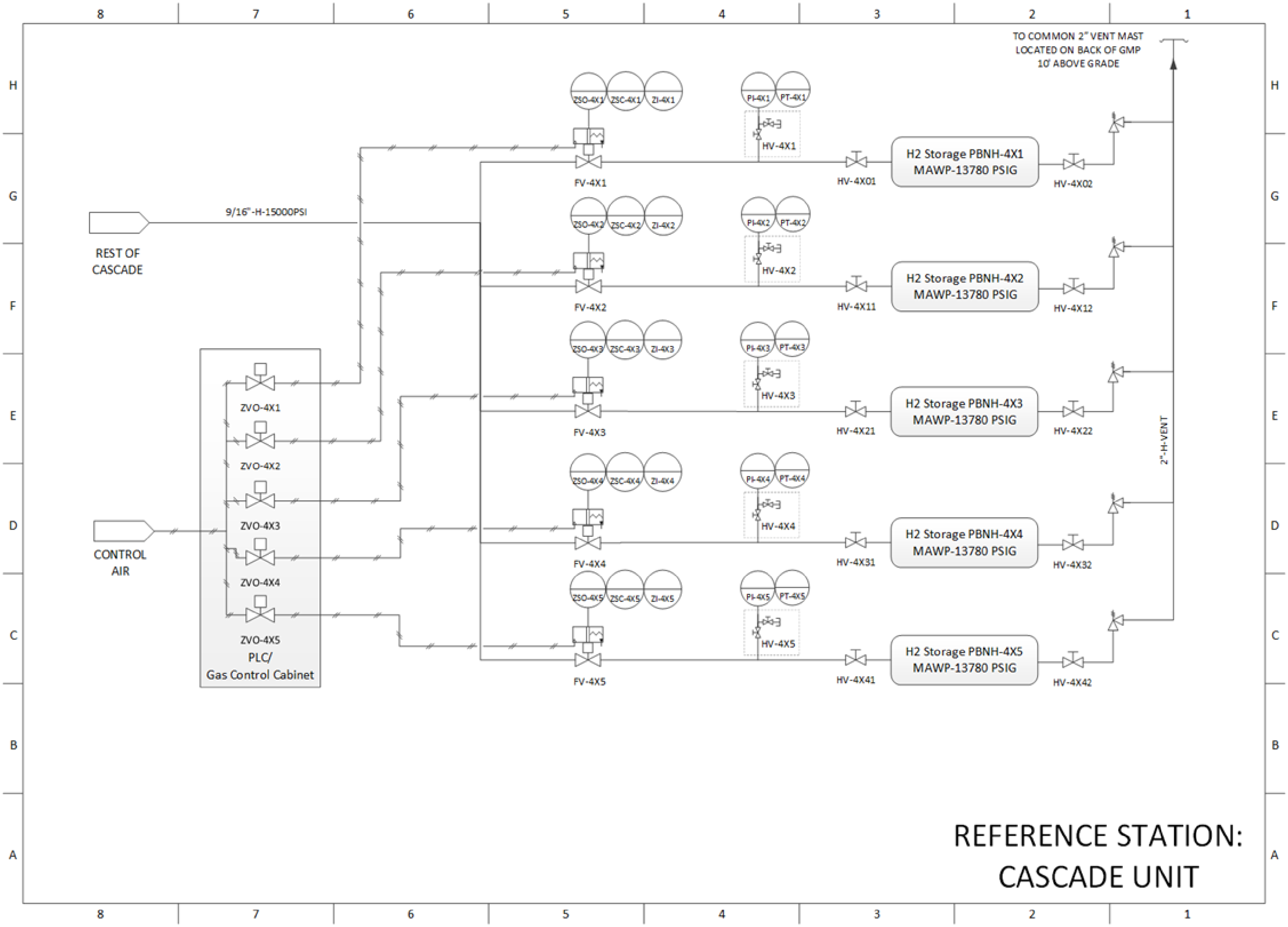
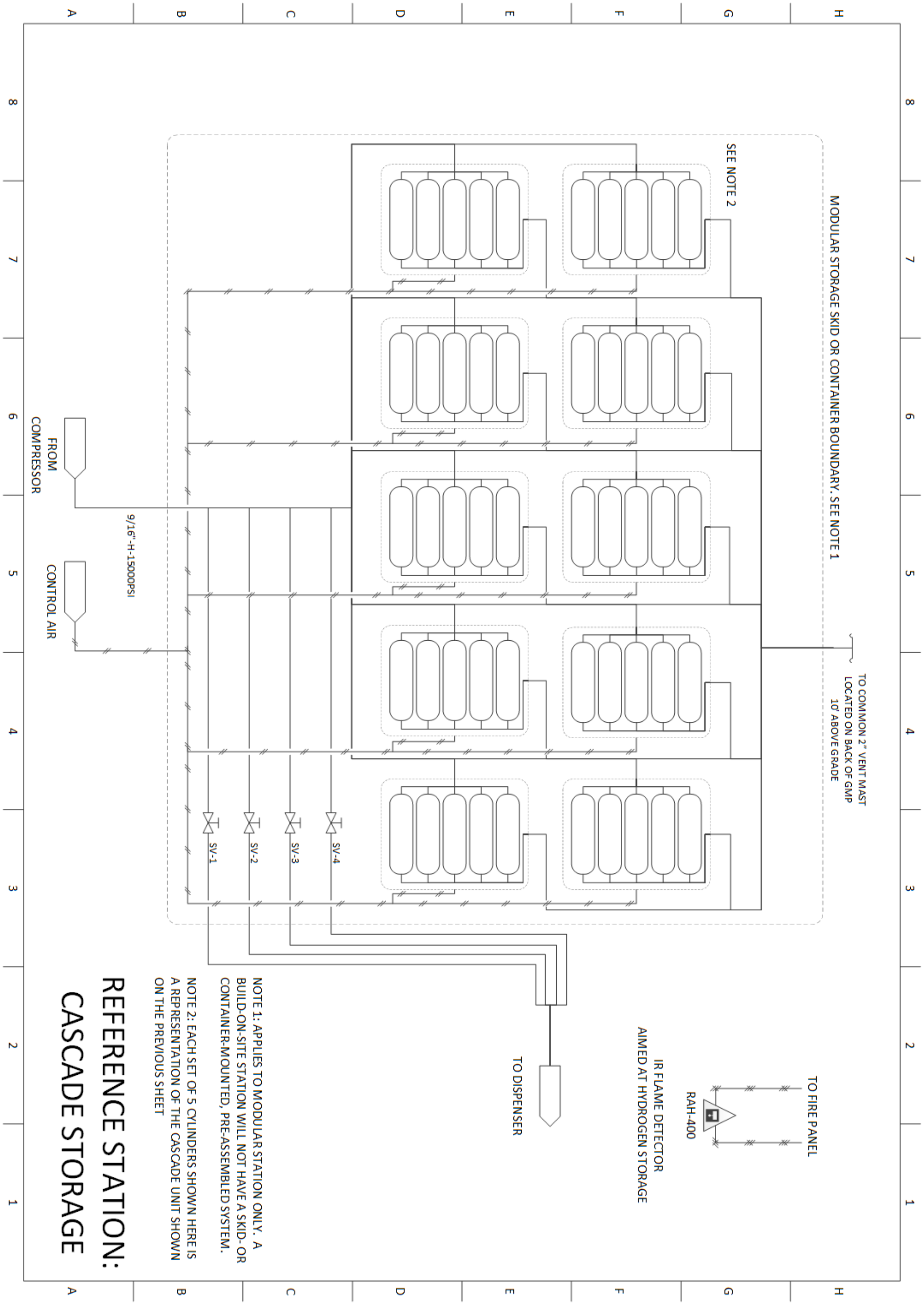


Figure A-6 Reference station P&ID 600 kg/day cascade storage subsystem [75]



NOTE 1: APPLIES TO MODULAR STATION ONLY. A BUILD-ON-SITE STATION WILL NOT HAVE A SKID- OR CONTAINER-MOUNTED, PRE-ASSEMBLED SYSTEM.

NOTE 2: EACH SET OF 5 CYLINDERS SHOWN HERE IS A REPRESENTATION OF THE CASCADE UNIT SHOWN ON THE PREVIOUS SHEET

REFERENCE STATION: CASCADE STORAGE

Figure A-7 Reference station P&ID 600 kg/day dispensing subsystem [75]

A.4. H2First 600kg/day liquid delivery station [75]

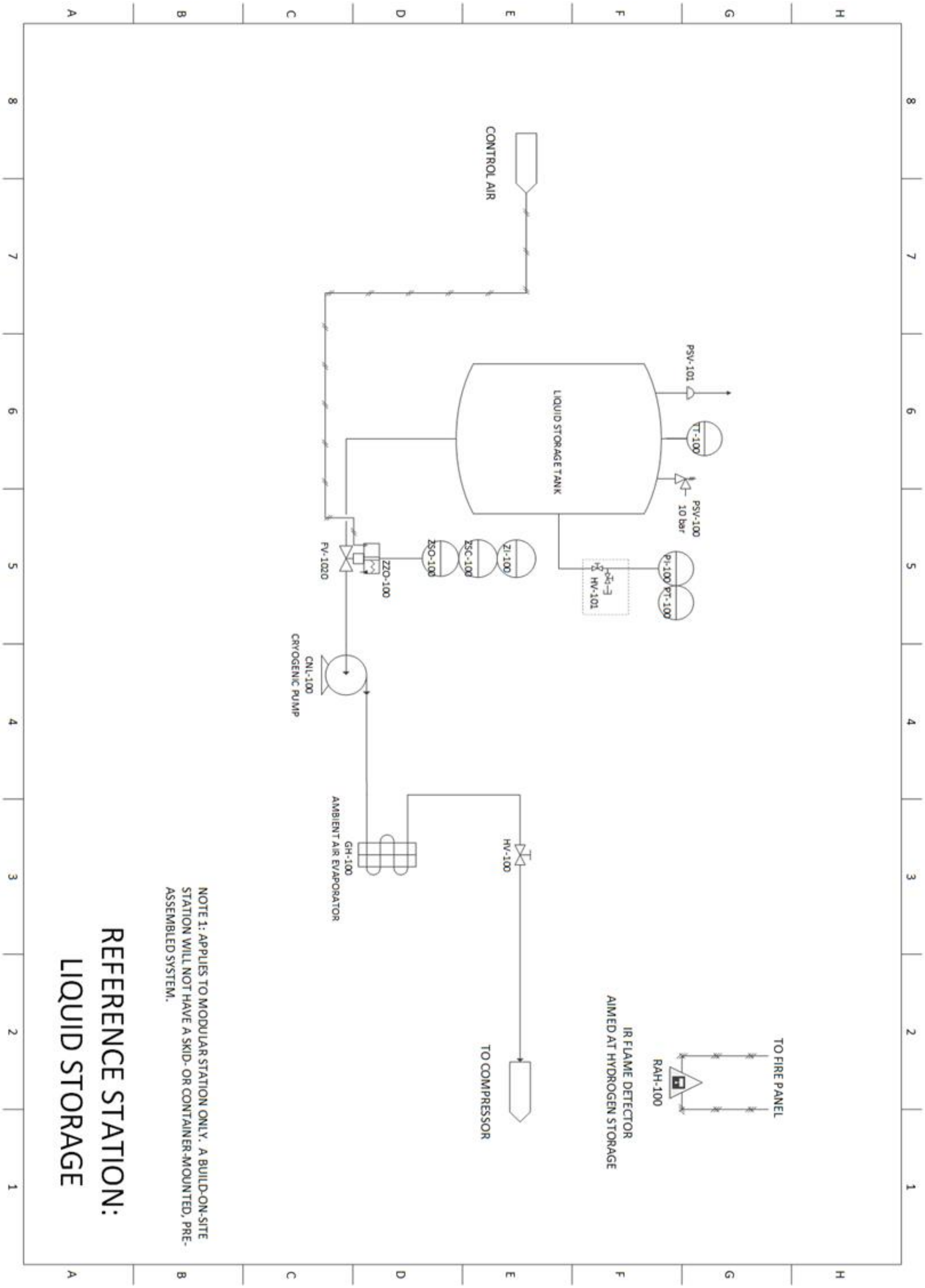


Figure A-8 Reference station P&ID 600 kg/day liquid delivery storage subsystem [75]

**See Figure A 5-7 for the 600kg/day liquid storage station compression and cooling, cascade storage, and dispensing subsystems respectively. These subsystems are the same as the 600kg/day gaseous delivery station because the stations were designed modularly so that different delivery methods could be used.

A.5. Japanese gaseous delivery station [23]

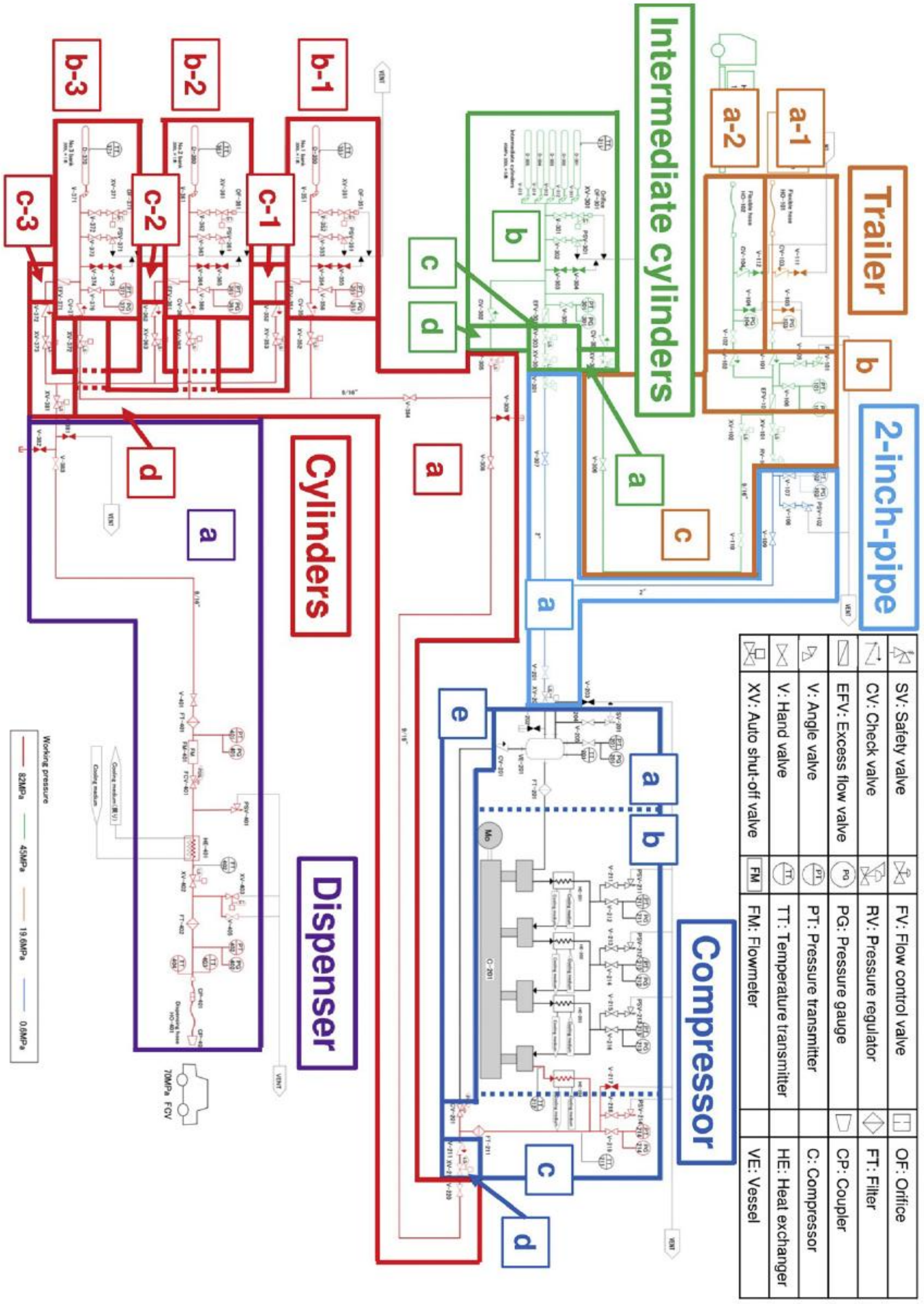


Figure A-9 Reference station P&ID Japanese gaseous delivery station [23]

Appendix B. Representative Hydrogen Fueling Station Subsystem Decompositions

B.1. Netherlands hydrogen fueling station subsystem decomposition

Table A-1 Netherlands hydrogen fueling station subsystem component decomposition developed from [10]

Netherlands hydrogen fueling stations							
Natural gas reformer	Water electrolyzer	Hydrogen pipeline	Tube/Cylinder trailer	Compressor/ Booster	Buffer storage	Pre-cooler/Heat exchanger	Dispenser
Reactor vessel	Electrolyzer stacks	Above ground pipeline	Pressurized tubes/Cylinders	Compressor/ Booster	Storage tubes/Cylinders	Pre-cooler/Heat exchanger	Cabinet
Desulphurization vessel	Purifier	Underground pipeline	Manifold				Metering device
Purifier	Heat exchanger		Flexible hose				Piping
Off gas vessel	Gas/liquid separator						Breakaway
Heat exchanger	Internal hydrogen storage vessel						Hose
Internal hydrogen storage vessel	External nitrogen cylinder						Nozzle
Natural gas compressor							Pressure relief device
External hydrogen and nitrogen vessels/cylinders							Communication interface

B.2. H2First 300kg/day gaseous delivery station subsystem decomposition

Table A-2 300kg/day gaseous hydrogen fueling station subsystem component decomposition developed from [74]

300 kg/day gaseous hydrogen fueling station					
Tube trailer gaseous storage	Compression	Cascade storage	Instrument air	Chiller	Dispensing
IR flame detector	Check valve	Hydrogen process pipe	Programmable logic control	Air cooled water chiller	Hydrogen process pipe
Pressure indicator	Pressure indicator	Hydrogen tank	Instrument air compressor	Coolant filter	Hydrogen cooling block
Pressure transmitter	Pressure transmitter	Hand valve	Instrument air receiver	Coolant pump	Air actuated flow valve
Hand valve	Hand valve	Bleed valve	Instrument air filter	Hydrogen chiller	Position indicator
Bleed valve	Air actuated flow valve	Pressure indicator	Instrument air dryer		Air operator
Delivery trailer	Position indicator	Pressure transmitter	Pilot solenoid valve		Position open
Air actuated flow valve	Air operator	Air actuated flow valve	Pneumatic signal line		Position closed
Position indicator	Position open	Position indicator			Bleed valve
Air operator	Position closed	Air operator			Hand valve
Position open	Motor	Position open			Hose
Position closed	Heater	Position closed			Nozzle
Hydrogen process pipe	Compressor	Pneumatic signal line			Emergency power off circuit
Check valve	Vent	Electric signal line			IR flame detector
Electric signal line	Filter	IR flame detector			Dispenser
Pneumatic signal line	Bleed valve				Dispenser controls
	Hydrogen process pipe				Electric signal line
	Pressure safety valve				Pneumatic signal line
	Pneumatic signal line				

B.3. H2First 300kg/day liquid delivery station subsystem decomposition

Table A-3 300kg/day liquid hydrogen fueling station subsystem component decomposition developed from [74]

300 kg/day liquid hydrogen fueling station					
Bulk liquid storage	Compression	Cascade storage	Instrument air	Chiller	Dispensing
IR flame detector	Check valve	Hydrogen process pipe	Programmable logic control	Air cooled water chiller	Hydrogen process pipe
Temperature transmitter	Pressure indicator	Hydrogen tank	Instrument air compressor	Coolant filter	Hydrogen cooling block
Pressure indicator	Pressure transmitter	Hand valve	Instrument air receiver	Coolant pump	Air actuated flow valve
Pressure transmitter	Hand valve	Bleed valve	Instrument air filter	Hydrogen chiller	Position indicator
Hand valve	Air actuated flow valve	Pressure indicator	Instrument air dryer		Air operator
Bleed valve	Position indicator	Pressure transmitter	Pilot solenoid valve		Position open
Cryogenic storage vessel	Air operator	Air actuated flow valve	Pneumatic signal line		Position closed
Air actuated flow valve	Position open	Position indicator			Bleed valve
Position indicator	Position closed	Air operator			Hand valve
Air operator	Motor	Position open			Hose
Position open	Heater	Position closed			Nozzle
Position closed	Compressor	Pneumatic signal line			Emergency power off circuit
Cryogenic pump	Vent	Electric signal line			IR flame detector
Ambient air evaporator	Filter	IR flame detector			Dispenser
Pressure safety valve	Bleed valve				Dispenser controls
Hydrogen process pipe	Hydrogen process pipe				Electric signal line
Check valve	Pressure safety valve				Pneumatic signal line
Electric signal line	Pneumatic signal line				
Pneumatic signal line					

B.4. H2First 600kg/day gaseous delivery station system decomposition

Table A-4 600kg/day gaseous hydrogen fueling station subsystem component decomposition developed from [75]

600 kg/day gaseous hydrogen fueling station					
Gaseous storage cylinders	Compression	Cascade storage	Instrument air	Chiller	Dispensing
Pressure indicator	Check valve	Hydrogen process pipe	Programmable logic control	Air cooled water chiller	Hydrogen process pipe
Pressure transmitter	Pressure indicator	Hydrogen tank	Instrument air compressor	Coolant filter	Hydrogen cooling block
Hand valve	Pressure transmitter	Hand valve	Instrument air receiver	Coolant pump	Air actuated flow valve
Bleed valve	Hand valve	Bleed valve	Instrument air filter	Hydrogen chiller	Position indicator
Hydrogen tank	Air actuated flow valve	Pressure indicator	Instrument air dryer		Air operator
Air actuated flow valve	Position indicator	Pressure transmitter	Pilot solenoid valve		Position open
Position indicator	Air operator	Air actuated flow valve	Pneumatic signal line		Position closed
Air operator	Position open	Position indicator			Bleed valve
Position open	Position closed	Air operator			Hand valve
Position closed	Motor	Position open			Hose
Pressure safety valve		Position closed			Nozzle
Hydrogen process pipe	Compressor	Pneumatic signal line			Emergency power off circuit
Pneumatic signal line	Vent	Electric signal line			IR flame detector
Vent	Filter	IR flame detector			Dispenser
Programmable logic control	Bleed valve	Vent			Dispenser controls
Pilot solenoid valve	Hydrogen process pipe	Pressure safety valve			Electric signal line
IR flame detector	Pressure safety valve				Pneumatic signal line
Electrical signal line	Pneumatic signal line				
	Electric signal line				
	IR flame detector				

B.5. H2First 600kg/day liquid delivery station system decomposition

Table A-5 600kg/day liquid hydrogen fueling station subsystem component decomposition developed from [75]

600 kg/day liquid hydrogen fueling station					
Bulk liquid storage	Compression	Cascade storage	Instrument air	Chiller	Dispensing
IR flame detector	Check valve	Hydrogen process pipe	Programmable logic control	Air cooled water chiller	Hydrogen process pipe
Temperature transmitter	Pressure indicator	Hydrogen tank	Instrument air compressor	Coolant filter	Hydrogen cooling block
Pressure indicator	Pressure transmitter	Hand valve	Instrument air receiver	Coolant pump	Air actuated flow valve
Pressure transmitter	Hand valve	Bleed valve	Instrument air filter	Hydrogen chiller	Position indicator
Hand valve	Air actuated flow valve	Pressure indicator	Instrument air dryer		Air operator
Bleed valve	Position indicator	Pressure transmitter	Pilot solenoid valve		Position open
Cryogenic storage vessel	Air operator	Air actuated flow valve	Pneumatic signal line		Position closed
Air actuated flow valve	Position open	Position indicator			Bleed valve
Position indicator	Position closed	Air operator			Hand valve
Air operator	Motor	Position open			Hose
Position open	Compressor	Position closed			Nozzle
Position closed	Vent	Pneumatic signal line			Emergency power off circuit
Cryogenic pump	Filter	Electric signal line			IR flame detector
Ambient air evaporator	Bleed valve	IR flame detector			Dispenser
Pressure safety valve	Hydrogen process pipe	Vent			Dispenser controls
Hydrogen process pipe	Pressure safety valve	Pressure safety valve			Electric signal line
Check valve	Pneumatic signal line				Pneumatic signal line
Electric signal line	Electric signal line				
Pneumatic signal line	IR flame detector				
Pressure relief device					

B.6. Japanese hydrogen fueling station subsystem decomposition

Table A-6 Japanese hydrogen fueling station subsystem component decomposition developed from [23]

Japanese hydrogen fueling station					
Trailer	2-inch pipe	Intermediate cylinders	Compressor	Cylinders	Dispenser
Gate valve	Gate valve	Cylinders	Pressure safety valve	Gate valve	Vent
Check valve	Pressure safety valve	Gate valve	Gate valve	Solenoid on off valve	Gate valve
Flexible hose	Pressure regulator	Temperature transmitter	Pressure transmitter	Check valve	Filter
Pressure gauge	Pressure transmitter	Solenoid on off valve	Pressure gauge	Excess flow valve	Flow meter
Pressure safety valve	Pressure gauge	Pressure safety valve	Temperature transmitter	Pressure transmitter	Pressure transmitter
Pressure transmitter	Solenoid on off valve	Manifold	Vessel	Pressure gauge	Pressure gauge
Solenoid on off valve	Hydrogen process pipe	Pressure transmitter	Filter	Temperature transmitter	Temperature transmitter
Excess flow valve		Pressure gauge	Motor	Cylinders	Flow control valve
Pressure regulator		Excess flow valve	Compressor	Orifice	Pressure safety valve
Hydrogen process pipe		Check valve	Heat exchanger	Vent	Heat exchanger
Cylinders		Angle valve	Flow control valve	Pressure safety valve	Solenoid on off valve
		Orifice	Check valve	Angle valve	Hose
		Hydrogen process pipe	Solenoid on off valve	Hydrogen process pipe	Breakaway coupling
			Hydrogen process pipe		Nozzle
					Hydrogen process pipe

Appendix C. Generic Hydrogen Component Hierarchy

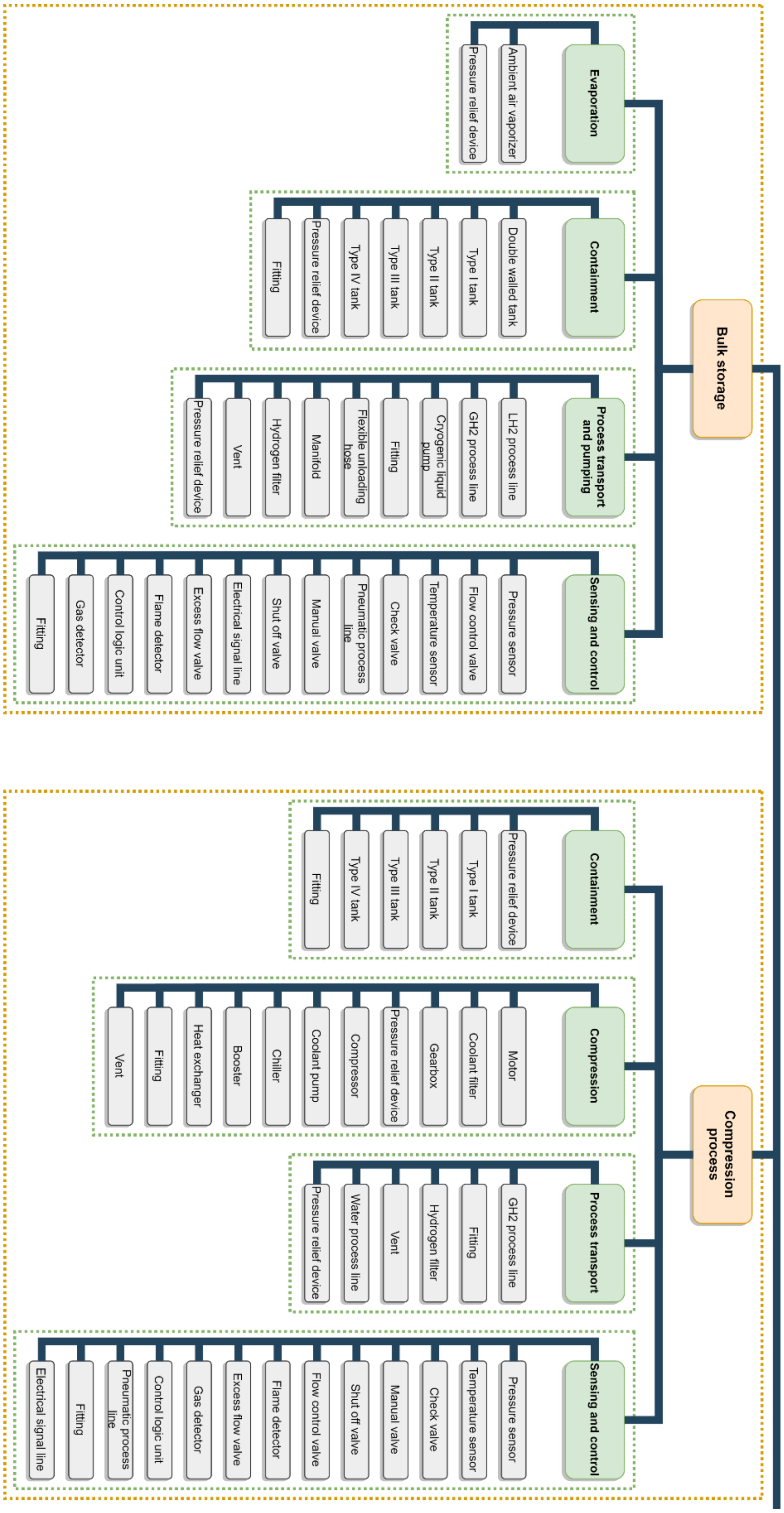


Figure A-10 Generic component hierarchy bulk storage and compression process subsystems

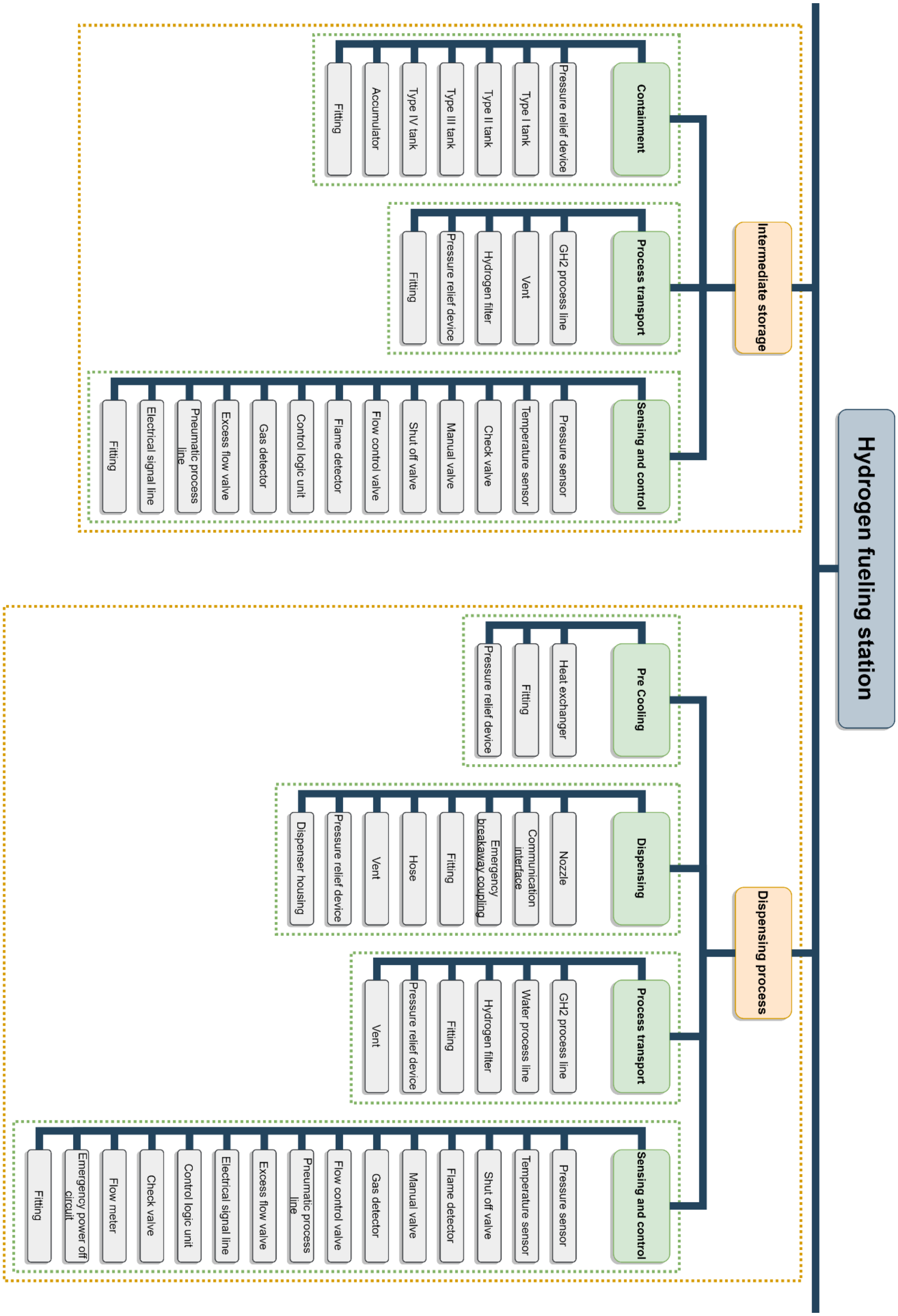


Figure A-11 Generic component hierarchy intermediate storage and dispensing process subsystems

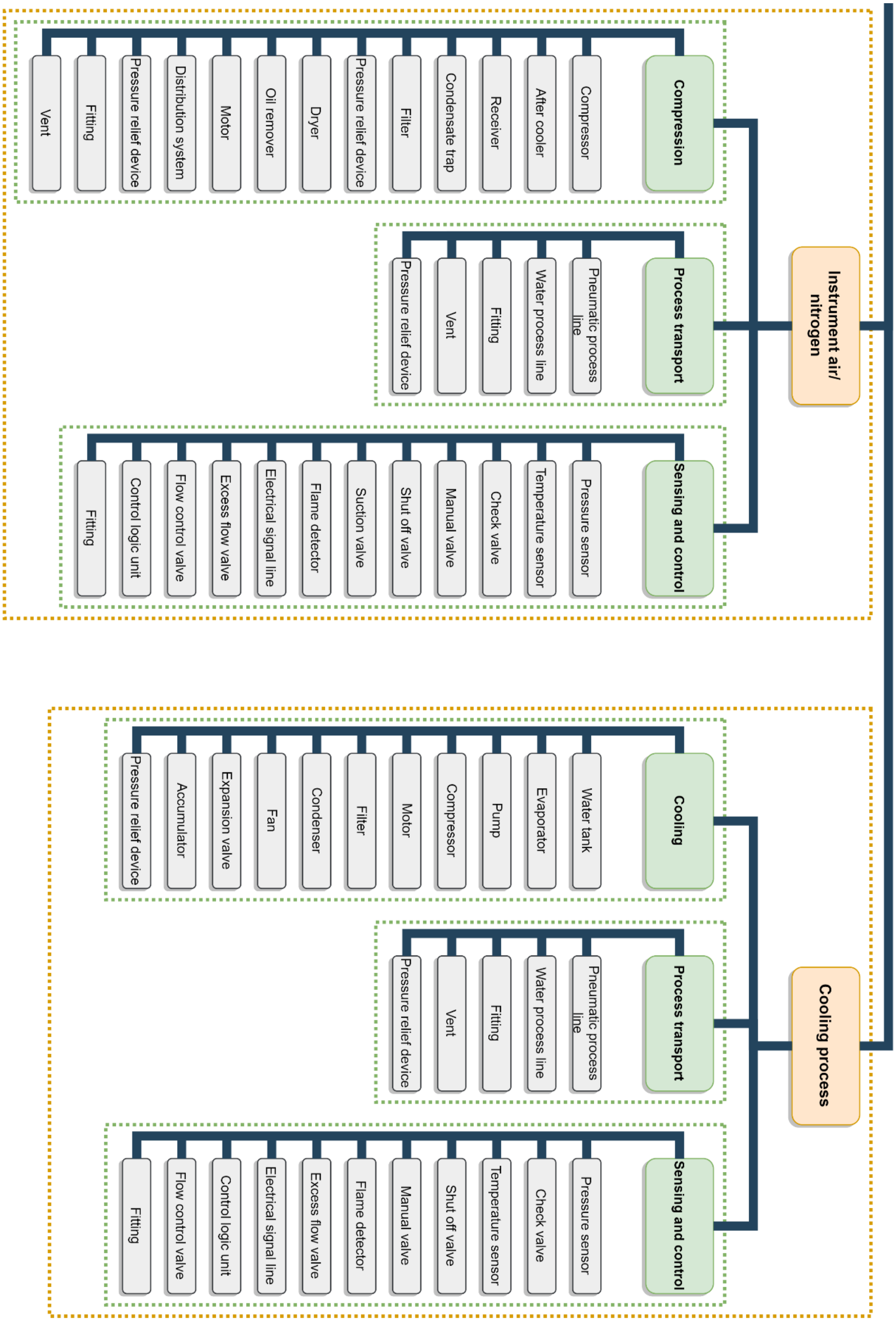


Figure A-12 Generic component hierarchy instrument air/ nitrogen and cooling subsystems

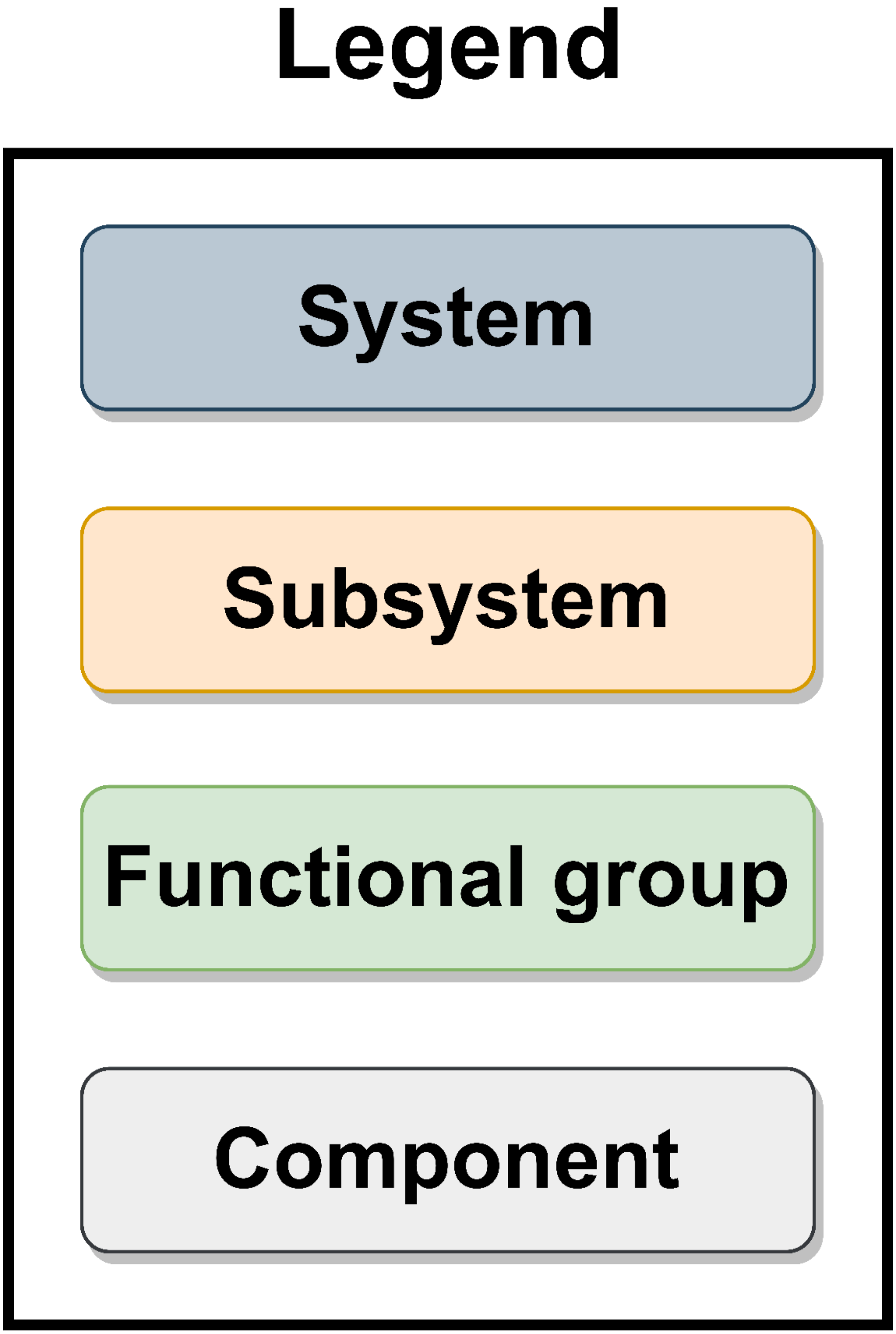


Figure A-13 Generic hydrogen component hierarchy legend

Appendix D. Hydrogen component failure mode taxonomy

Table A-7 Hydrogen component failure mode definitions

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 damage
Contamination	Component allows foreign material to contaminate product
Drift	Erroneous reading due to lack of calibration
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 disconnect	Components meant to disconnect does not do so on demand
Fail to evaporate	Hydrogen remains in liquid form after passing through evaporator
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
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
Overspeed	Component operates above desired/specified speed
Plugging	Buildup of material restricting flow
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)
Stuck connection	Component is stuck at point of contact (nozzle)
Underspeed	Component operates below desired/specified speed

Failure modes labeled in green have been specifically developed for hydrogen fueling station

Table A-8 Failure mode taxonomy containment functional group

Functional group	Containment						
Component	Double walled tank	Type 1 tank	Type 2 tank	Type 3 tank	Type 4 tank	Pressure relief device	Fitting
Failure modes	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen
	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen
	Internal leak hydrogen					Fail to close	
	Internal rupture hydrogen					Fail to operate	
						Spurious operation	

Table A-9 Failure mode taxonomy evaporation functional group

Functional group	Evaporation	
Component	Ambient air evaporator	Pressure relief device
Failure modes	External leak hydrogen	External leak hydrogen
	External rupture hydrogen	External rupture hydrogen
	Fail to evaporate	Fail to close
	Plugging	Fail to operate
		Spurious operation

Table A-10 Failure mode taxonomy pre-cooling functional group

Functional group	Pre-cooling		
Component	Heat exchanger	Fitting	Pressure relief device
Failure modes	External leak hydrogen	External leak hydrogen	External leak hydrogen
	External leak utility medium	External rupture hydrogen	External rupture hydrogen
	External rupture hydrogen		Fail to close
	External rupture utility medium		Fail to operate
	Insufficient heat transfer		Spurious operation
	Plugging		

Table A-11 Failure mode taxonomy process transport and piping functional group

Functional group	Process transport and piping									
Component	LH2 Process Line	GH2 Process line	Cryogenic liquid pump	Fitting	Flexible unloading hose	Manifold	Hydrogen filter	Vent	Pressure relief device	Water process line
Failure modes	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen	External leak hydrogen	Contamination	Plugging	External leak hydrogen	External leak utility medium
	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen	Plugging		External rupture hydrogen	External rupture utility medium
	Plugging	Plugging	Fail to operate		Plugging	Plugging			Fail to close	Plugging
			Fail to stop						Fail to operate	
			Internal leak hydrogen						Spurious operation	
			Internal rupture hydrogen							
			Noise							
			Overheating							
			Overspeed							
			Plugging							
			Spurious operation							
			Spurious stop							
			Underspeed							
			Vibration							

Table A-12 Failure mode taxonomy compression functional group

Functional group	Compression								
Component	Motor	Coolant filter	Gearbox	Pressure relief device	Compressor	Booster	Heat exchanger	Fitting	Vent
Failure modes	Fail to operate	Contamination	Fail to operate	External leak hydrogen	Contamination	External leak hydrogen	External leak hydrogen	External leak hydrogen	Plugging
	Fail to stop	Plugging	Noise	External rupture hydrogen	External leak hydrogen	External rupture hydrogen	External leak utility medium	External rupture hydrogen	
	Noise		Overheating	Fail to close	External leak utility medium	Fail to operate	External rupture hydrogen		
	Overheating		Vibration	Fail to operate	External rupture hydrogen	Fail to stop	External rupture utility medium		
	Overspeed			Spurious operation	External rupture utility medium	Internal leak hydrogen	Insufficient heat transfer		
	Spurious operation				Fail to operate	Internal rupture hydrogen	Plugging		
	Spurious stop				Fail to stop	Overspeed			
	Underspeed				Internal leak hydrogen	Plugging			
	Vibration				Internal rupture hydrogen	Spurious operation			
					Noise	Spurious stop			
					Overheating	Underspeed			
					Overspeed	Vibration			
					Spurious operation				
					Spurious stop				
					Underspeed				
					Vibration				

Table A-13 Failure mode taxonomy dispensing functional group

Functional group	Dispensing							
Component	Nozzle	Communication interface	Emergency breakaway coupling	Fitting	Hose	Vent	Pressure relief device	Dispenser housing
Failure modes	Bent warped damaged	Bent warped damaged	External leak hydrogen	External leak hydrogen	External leak hydrogen	Plugging	External leak hydrogen	Bent warped damaged
	External leak hydrogen	Erratic output	External rupture hydrogen	External rupture hydrogen	External rupture hydrogen		External rupture hydrogen	
	External rupture hydrogen	Fail to operate	Fail open		Plugging		Fail to close	
	Fail closed		Fail to disconnect		Stuck connection		Fail to operate	
	Fail open						Spurious operation	
	Fail to operate							
	Fail to stop							
	Operation error							
	Plugging							
	Spurious operation							
	Stuck connection							

Table A-14 Failure mode taxonomy sensing and control functional group

Functional group	Sensing and control							
Component	Pressure sensor	Flow control valve	Temperature sensor	Check valve	Pneumatic process line	Manual valve	Shut-off valve	Electrical signal line
Failure modes	Abnormal output-high	External leak hydrogen	Abnormal output-high	External leak hydrogen	External leak utility medium	External leak hydrogen	External leak hydrogen	Open circuit
	Abnormal output-low	External rupture hydrogen	Abnormal output-low	External rupture hydrogen	External rupture utility medium	External rupture hydrogen	External rupture hydrogen	Short circuit
	Drift	Fail closed	Drift	Fail close	Plugging	Fail close	Fail closed	
	Erratic output	Fail open	Erratic output	Fail open		Fail open	Fail open	
	External leak hydrogen	Fail to operate	External leak hydrogen	Internal leak hydrogen		Internal leak hydrogen	Fail to operate	
	External rupture hydrogen	Internal leak hydrogen	External rupture hydrogen	Internal rupture hydrogen		Internal rupture hydrogen	Internal leak hydrogen	
	Fail to operate	Internal rupture hydrogen	Fail to operate	Plugging		Plugging	Internal rupture hydrogen	
		Plugging		Restrict flow		Restrict flow	Plugging	
		Restrict flow					Restrict flow	
		Spurious operation					Spurious operation	

Table A-15 Failure mode taxonomy sensing and control functional group continued

Functional group	Sensing and control						
Component	Excess flow valve	Flame detector	Control logic unit	Gas detector	Fitting	Flow meter	Emergency power off circuit
Failure modes	External leak hydrogen	Abnormal output-high	Abnormal output-high	Abnormal output-high	External leak hydrogen	Drift	Open circuit
	External rupture hydrogen	Abnormal output-low	Abnormal output-low	Abnormal output-low	External rupture hydrogen	Erratic output	Short circuit
	Fail close	Drift	Erratic output	Drift		Fail to operate	
	Fail open	Erratic output	Fail to operate	Erratic output			
	Internal leak hydrogen	Fail to operate	Spurious operation	Fail to operate			
	Internal rupture hydrogen						
	Plugging						
	Restrict flow						

Table A-16 Failure mode taxonomy air/nitrogen compression functional group

Functional group	Air/ nitrogen compression								
Component	Compressor	After cooler	Receiver	Condensate trap	Filter	Pressure relief device	Fitting	Vent	Suction valve
Failure modes	Contamination	External leak utility medium	External leak utility medium	Contamination	Contamination	External leak utility medium	External leak utility medium	Plugging	External leak utility medium
	External leak utility medium	External rupture utility medium	External rupture utility medium	External leak utility medium	Plugging	External rupture utility medium	External rupture utility medium		External rupture utility medium
	External rupture utility medium	Insufficient heat transfer		External rupture utility medium		Fail to close			Fail closed
	Fail to operate	Plugging		Plugging		Fail to operate			Fail open
	Fail to stop					Spurious operation			Fail to operate
	Internal leak utility medium								Internal leak utility medium
	Internal rupture utility medium								Internal rupture utility medium
	Noise								Plugging
	Overheating								Restrict flow
	Overspeed								Spurious operation
	Spurious operation								
	Spurious stop								
	Underspeed								
	Vibration								

Table A-17 Failure mode taxonomy cooling functional group

Functional group	Cooling										
Component	Water tank	Evaporator	Pump	Compressor	Motor	Filter	Condenser	Fan	Expansion valve	Accumulator	Pressure relief device
Failure modes	External leak utility medium	External leak utility medium	External leak utility medium	Contamination	Fail to operate	Contamination	External leak utility medium	Fail to operate	External leak utility medium	External leak utility medium	External leak utility medium
	External rupture utility medium	External rupture utility medium	External rupture utility medium	External leak utility medium	Fail to stop	Plugging	External rupture utility medium	Fail to stop	External rupture utility medium	External rupture utility medium	External rupture utility medium
		Insufficient heat transfer	Fail to operate	External rupture utility medium	Noise		Insufficient heat transfer	Noise	Fail close	Fail closed	Fail to close
		Plugging	Fail to stop	Fail to operate	Overheating		Plugging	Overspeed	Fail open	Fail open	Fail to operate
			Internal leak utility medium	Fail to stop	Overspeed			Spurious operation	Internal leak utility medium	Internal leak utility medium	Spurious operation
			Internal rupture utility medium	Internal leak utility medium	Spurious operation			Spurious stop	Internal rupture utility medium	Internal rupture utility medium	
			Noise	Internal rupture utility medium	Spurious stop			Underspeed	Plugging		
			Overheating	Noise	Underspeed			Vibration	Restrict flow		
			Overspeed	Overheating	Vibration						
			Plugging	Overspeed							
			Spurious operation	Spurious operation							
			Spurious stop	Spurious stop							
			Underspeed	Underspeed							
			Vibration	Vibration							

References

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