OVERVIEW OF INTERNATIONAL ACTIVITIES IN HYDROGEN SYSTEM SAFETY IN IEA HYDROGEN TCP TASK 43

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ABSTRACT

Safety and reliability have long been recognized as key issues for the development, commercialization, and implementation of new technologies and infrastructure, and hydrogen systems are no exception to this rule. Reliability engineering, quantitative risk assessment (QRA), and knowledge exchange each play a key role in proactive addressing safety – *before* problems happen – and help us learn from problems *if* they happen. Many international research activities are focusing on both reliability and risk assessment for hydrogen systems. However, the element of knowledge exchange is sometimes less visible. To support international collaboration and knowledge exchange, the International Energy Agency (IEA) convened a new Technology Collaboration Program, "Task 43: Safety and Regulatory Aspects of Emerging Large Scale Hydrogen Energy Applications" started in June 2022. Within Task 43, Subtask E focuses on Hydrogen Systems Safety. This paper discusses the structure of the Hydrogen Systems Safety subtask and the aligned activities and introduces opportunities for future work.

1. INTRODUCTION

The International Energy Agency (IEA) Hydrogen Technology Collaboration Program (TCP) has organized a new task, Task 43 “Safety and Regulatory Aspects of Emerging Large Scale Hydrogen Energy Applications,” aimed at sharing information regarding hydrogen safety. IEA Hydrogen Task 43 aims to develop effective data, models, and methodologies to enable risk management and develop recommendations via case studies and data analysis to create targeted information products that will facilitate the accelerated market penetration of large-scale hydrogen energy systems. In Task 43, hydrogen systems are defined as large-scale in view of involving widespread deployment (e.g., large numbers of systems) or in terms of system or facility size.

Task 43 continues a legacy of hydrogen safety activities within the IEA TCPs. The first IEA Hydrogen TCP Task on Hydrogen Safety was originally launched in October 2004 under the IEA HIA framework as Task 19. Its conception was prompted by the initiation of hydrogen safety R&D programs in the USA, Canada, the European Union, and Japan. It thus provided an excellent platform for information exchange and the start of new international collaborations in the hydrogen safety field. The focus of Task 19 was to develop landmark recommendations for risk and harm criteria for use of hydrogen technologies as well as to advance the fundamental and applied research on hydrogen behavior. The successor Tasks 31 and 37 continued on the same path, enriching the knowledge and closing gaps regarding hydrogen properties as well as further enhancing the elements of quantitative risk assessment (QRA) and system safety.

As efforts to deploy clean energy technologies have come to the forefront of policy around the globe, significant hydrogen deployments are anticipated. Global regulatory bodies like UN ECE, IMO, ICAO, and national rail administrations have set aggressive targets to reduce the carbon footprint of ground vehicles, rail, maritime, and aviation fleets by 2050, along with the large-scale infrastructure necessary to support their deployment. As a result, new hydrogen energy applications are being developed and deployed at a large scale. The scale of these developments brings new urgency to addressing hydrogen safety topics proactively. A safe and sustainable transition to expanded hydrogen usage requires that the risks associated with hydrogen systems be proactively and rigorously investigated, quantified, and mitigated – at the design and early deployment stage when it is cheapest and easiest to make engineering changes.

To support international collaboration and knowledge exchange, the IEA, under the TCP, convened a new Task 43 “Safety and Regulatory Aspects of Emerging Large Scale Hydrogen Energy Applications” with an operating term of June 1, 2022 to May 31, 2025. Within Task 43, Subtask E focuses on Hydrogen Systems Safety, drawing together efforts to advance the state of the art in reliability engineering, risk analysis, and system safety for hydrogen systems. This paper discusses the motivation and structure of the Hydrogen Systems Safety subtask and the aligned activities, and introduces opportunities for future work.

2. OBJECTIVES AND STRUCTURE OF SUBTASK

Subtask E provides a forum for exchanging scientific information regarding hydrogen system safety and addressing technical gaps pertaining to the safety, risk, and reliability analysis of these systems. The subtask is structured around four essential activities, each designed to fill a core gap identified by Moradi and Groth [1]: Reliability data collection and curation (E1), improvements to current hydrogen QRA tools (E2), developing advanced QRA and prognostics methods (E3), and conducting analyses of hydrogen systems (e.g., case studies, E4). Subtask E is designed to create scientific outputs that support the development of requirements, codes, standards, and best practice recommendations for the safe operation of hydrogen systems, and the Subtask E results will be fed into Subtask F to create industry guidance and input to requirements, codes, standards, and best practices.

The emphasis is on insights for the safe operation of compressed gaseous and liquid hydrogen energy systems involving mechanical and process equipment or vehicles. Anticipated applications include equipment and vehicles in confined environments such as hydrogen equipment enclosures, repair facilities, underground parking structures, and related deployments.

Subtask E is led by Katrina Groth at the University of Maryland, USA. The structure of the Subtask is shown in Figure 1. Participating organizations were identified at the first Task 43 meeting in Buxton, UK in October 2022 and the second meeting in Golden, Colorado, USA in March 2023. The following organizations have expressed interest in participating in Subtask E: Arup; Air Liquide; Airbus Operations Limited; Canadian Nuclear Labs; DGC a/s; DTU Construct; Engie; HSE; Hydrogen Council; ITM Power; Lifte H2 GmbH; Lloyd's Register; Lund University; National Renewable Energy Laboratory (NREL); Norwegian University of Science and Technology (NTNU); Shell; University of Bergen (UiB); University of Maryland (UMD) Center for Risk and Reliability; University of South-Eastern Norway (USN); University of Stavanger (UiS); Ulster University, HySAFER Centre.

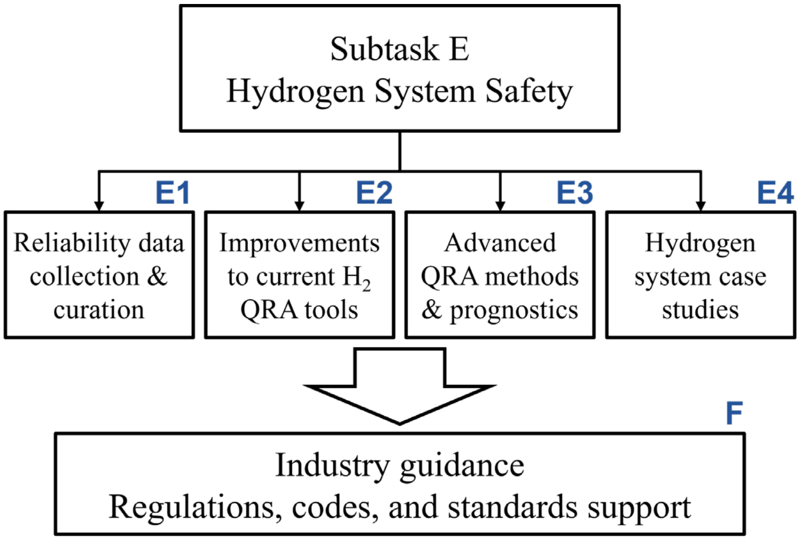

Figure 1: Structure of Subtask E, Hydrogen System Safety

3. ALIGNED ACTIVITIES

E1 Reliability data collection and curation for hydrogen systems

Activities under this topic seek to build reliability data collection frameworks and collect and curate data for hydrogen system QRA and reliability studies. Data collection and curation is a well-known and high priority gap for hydrogen safety [1]. These activities are important inputs to QRA tools such as the HyRAM algorithm [2] and HyRAM+ software [3]. Recently, the University of Maryland (UMD) and the NREL conducted a detailed assessment of current hydrogen safety databases and QRA literature, including HIAD [4], the NREL CDPs, and H2Tools Lessons Learned with regards to suitability for use in hydrogen QRA [5]. They also reviewed QRA data collection strategies, best practices, and databases from other industries with more mature QRA and reliability engineering methods and concluded that widely used databases in other industries lacked hydrogen component and system data. Based on these results, the existing databases are not suitable for supporting QRA for hydrogen systems but provide meaningful points for future research [5,6,7]. In response, the IEA hydrogen community's research projects that seek to address this gap are timely and relevant.

UMD and NREL have created the HyCReD (Hydrogen Component Reliability Database) project with a detailed, carefully defined reliability data collection framework for hydrogen components, focusing initially on hydrogen fueling stations [8, 9]. They developed 23 requirements for the proposed database. The resulting HyCReD framework meets these requirements and includes a detailed description of 25 data elements spanning system description, equipment descriptions, event data (e.g., failure events and near misses), and maintenance events. They also developed a taxonomy of hydrogen component decompositions for fueling stations and identified and defined a comprehensive set of relevant failure modes for the major components of each system. The data elements were defined according to international standards used in the safety and reliability practice and potential choice lists are provided for each field. Since this database is being piloted for hydrogen fueling stations, a generic station component hierarchy developed by West (2021) was used to standardize system data. The next logical step is to identify industry collaboration opportunities that can provide data for populating the database, focusing on hydrogen fueling stations.

Although the collection of incident data, as described above, provides important data for leak frequency estimation, it can potentially introduce a bias since the denominator (the number of component-years of exposure) can be underestimated since facilities without incidents are often not included in such databases. Therefore, Lund University is conducting work that will complement the database with data from a small but well-controlled environment. The data will be collected prospectively from a HRS developer as they launch 24 stations over the two coming years. Component counts will be provided and, in case of a leakage, an interview will be held to collect detailed information about the event. UMD is also in the process of developing agreements with a HRS partner to collect comprehensive station operation, incident, and maintenance data.

The Hydrogen Council is also in the process of setting up an internal task team to collect data on failure rates/leakage frequencies related to hydrogen production and use by the Council members. The information will be collected on an anonymous basis and generalized for further analysis within E1 activities. Similar activities are under discussion within the Center for Hydrogen Safety. The authors are also aware of additional activities, including the UK Energy Institute working group HY2203 which is looking into hydrogen incident databases.

Vysus Group is a partner in a project named SAFEN that aims at developing more reliable data regarding leakage frequencies (for hydrogen, ammonia, and CO_2; gaseous and liquified) and ignition probability (for hydrogen and ammonia). The project has 5 work packages including one on data collection, failure mode analysis (including the development of an overview of the kind of technical equipment that is being used), and ignition mechanisms and ignition probability. The overall aim is to improve the current models available for these three substances (hydrogen has the priority) including PLOFAM (for leakage frequencies in the oil and gas industry) and HyRAM. The project has contact with Sandia National Laboratories and established a collaboration with a project on similar topics but only regarding hydrogen fueling stations run by INERIS in France.

ENGIE with Air Liquide, Shell, ITM Power, HSE and INERIS, are involved in MultHYfuel project [10] to establish best practices for the implementation of hydrogen dispenser in a multifuel context. In this project, work package 2 will develop models to predict the likelihood and size of hydrogen leakage from a dispenser and experimentations on dispenser accessories and fittings (e.g., the cycle of pressure and temperature, wrong tightening) during the first half of 2023.

On the experimental side, the USN is preparing a test setup for experimental investigations and numerical model development of a novel leak detection system for maritime hydrogen pipe systems. The work is carried out within the HyLOCD project sponsored by the Norwegian Research Council. Related activities are ongoing at NREL by conducting experimental characterization of leaks through the Leak Rate

Quantification Apparatus (LQRA) and connecting those to QRA activities for the U.S. Department of Energy [11].

E2 Improvements to current hydrogen QRA tools

Activities under this topic seek to improve upon the current QRA methods and tools used in hydrogen applications (e.g., HyRAM+ [3]) and advance the technical basis of conducting QRAs for hydrogen safety. The HyRAM (now HyRAM+) toolkit has become an important tool for hydrogen safety by integrating and freely disseminating the state of the art in hydrogen safety models and data for QRA. HyRAM was conceptualized and developed by Sandia National Laboratories for the U.S. Department of Energy to draw together decades of hydrogen safety research [2]. Beginning as an internal Sandia tool, it was conceptualized by Groth in 2012 to address the lack of freely available, simplified engineering tools and support for conducting the early QRAs for hydrogen fueling stations. The HyRAM software was first released publicly in December 2014 as HyRAM 1.0alpha, and has been continually improved since, with the latest version HyRAM+ 5.0 released in November 2022. Sandia continues to expand HyRAM+ and disseminates it as a free, open source tool.

Important work in this area includes developing the technical basis of failure rates and probabilities used in the tools, adding new models to the tools, enhancing the usability of existing tools, and expanding the tools in scope and depth. The development of improved failure rates and probabilities for component failures are closely connected to the activities described in task E1. The authors are also aware of some efforts to develop more advanced ignition probability models including conditional ignition probability (probability of ignition given exposure to a flammable mixture), discrete and continuous ignition sources and immediate vs delayed ignition models under activities such as the MISOF (Modelling of Ignition Sources on Offshore oil and gas Facilities) project [12]. There are also many relevant experimental and modeling activities occurring under Subtask D (Hazardous Areas Classification) which are relevant to ignition probabilities.

Work at UMD is focusing on identifying gaps in available QRA data and models for a variety of hydrogen technologies. Two recent UMD studies used a combination of Failure Modes and Effects Analysis (FMEA), event sequence diagrams models, fault tree analysis, cut-sets, importance measures, and connected them to hydrogen release, behavior, and flame simulations developed in HyRAM. The study by [13] found that the HyRAM methodology [2] was mature and robust enough to develop actionable, defensible insights about hydrogen forklifts, however, the HyRAM+ toolkit [3] needs to be expanded to integrate capabilities to conduct fault tree analysis and event sequence modeling. Correa-Jullian and Groth [6] conducted a QRA on a liquid hydrogen storage system for on-site storage at a fueling station, to identify relevant scenario and probability data currently available and ascertaining future data collection requirements regarding risks specific to liquid hydrogen releases. They found that component failure and reliability data are still limited, especially in the context of liquid and cryogenic components, and suggested new methods to address these limitations (motivating studies discussed in E1 and E3). Additional gaps were found that point to a need for further development of ignition models, release models and behavior models for liquid hydrogen. There is also a need for more physics of failure studies on hydrogen components. UMD is currently conducting similar gap studies for the Low Carbon Resources Initiative (LCRI), focusing on identifying QRA data and QRA tool gaps for electrolyzers, storage, and pipelines.

A QRA toolkit is being developed for hydrogen systems using MATLAB at the Canadian Nuclear Laboratories (CNL). The toolkit has adopted the analysis approach implemented in Sandia's HyRAM software. The toolkit estimates the fatality likelihood and impacts of exposure to radiant heat flux from a jet fire and overpressure-impulse from an explosion. Verification and validation exercises were conducted by comparing CNL's model predictions for hazard distances and risk metrics with the HyRAM calculations. A QRA case study was carried out for a hydrogen locomotive that estimates risks for loss of life, accident rate, and individual risk and results are detailed by [14]. The sensitivity parameter studies demonstrated the importance of immediate detection and isolation of a leak. Corrective and preventative action plans, such as routine scheduled maintenance of the components, are critical to prevent the most damaging leak incident and stop the recurrence of smaller leaks. The toolkit will be extended to include liquid hydrogen and blends in the future. Additional physics models will be added based on the computational fluid dynamics modeling results and experimental data.

The Norwegian University of Science and Technology (NTNU) is spearheading a project titled *'SUS*tainability and cost-reduction of *Hy*drogen stations through risk-based, multidisciplinary approaches'—dubbed *'SUSHy Project'* for short [15]. SUSHy Project launched last spring and it is a three-year European-Japanese research project, with partner research institutions NTNU (Norway), Silesian University of Technology (SUT, Poland), Centre for Energy, Environmental and Technological Research (CIEMAT, Spain), Niğde Ömer Halisdemir University (NOHU, Turkey) and Nagoya University (NU, Japan). It received funding through the European Interest Group (EIG) CONCERT-Japan platform, an international joint initiative to enhance science, technology and innovation cooperation between European countries and Japan. This project includes a work package on hybrid renewable-energy-powered (HREP) hydrogen stations, led by SUT, is developing a framework to identify typical and atypical accident scenarios related to hydrogen systems that may lead to uncontrolled releases of hydrogen, especially considering those that directly endanger nearby communities and the neighboring environment. Such accident scenarios and their probability of occurrence will be estimated using statistical data and QRA methods including FMEA and fault trees. The consequences of dangerous events such as heat radiation and overpressure will be assessed through analytical models (e.g., HyRAM). To further enhance the validity of calculations for critical system components in the hydrogen stations additional computations will be performed using techniques of Finite Elements Analysis (FEA) and Computational Fluid Dynamics (CFD).

University Roma Sapienza and DTU Construct developed a QRA based risk methodology to evaluate the risk of hydrogen vehicles in road and rail tunnels as well as in car parks [16]. The methodology has been applied to the respective areas through case studies. The activity has been part of the EU Clean Hydrogen Partnership project HyTunnel CS- Pre-normative research for the safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces (project no. 826193).

Lund University is currently developing a novel model for simulating hydrogen accumulation in enclosures based on the multi-zone concept [17]. This model can be used to estimate, for example, the probability of hazardous overpressures in enclosures, accounting for variations in leak sizes, directions, and locations, using a Monte-Carlo based approach. It can also be used to estimate the distribution of time for detector activation and similar important input to the consequence estimation. Lund University is actively exploring possibilities for connection to tools such as HyRAM+.

SINTEF, NTNU, UiB, UiS, USN, RISE, Gexcon, KIT and Demokritos participate in the Norwegian project *Safe Hydrogen Fuel Handling and Use for Efficient Implementation 2* (SH2IFT-2), which aims to close critical knowledge gaps concerning the safe use of hydrogen equipment. Specific focus is given to hydrogen leaks, fires, and explosions through the development (and refinement) of existing modeling tools and a vast experimental campaign on different scales. The consequence analysis concerning the ignition of hydrogen-air mixtures in realistic release scenarios is conducted in connection with the assessment of failure frequencies. The hydrogen-induced material degradation lies in fact at the core of the project, with a specific task led by NTNU that aims at defining the risk-based operational safety of hydrogen technologies.

NTNU is also coordinating the European project ELVHYS (Enhancing the safety of liquid and vaporized hydrogen transfer technologies in public areas for mobile applications). ELVHYS aims to provide indications on inherently safer and efficient cryogenic and liquid hydrogen technologies and protocols in mobile applications (e.g., trucks, ships, fueling stations) by proposing innovative safety strategies including the selection of effective safety barriers and hazard zoning strategies obtained through detailed QRA. This is carried out by applying an interdisciplinary approach and conducting experimental, theoretical, and numerical studies both on the cryogenic hydrogen transferring procedures and on the phenomena that may arise from the loss of containment of a piece of equipment containing hydrogen. Unique investigations on (i) cryogenic hydrogen transferring operations for selected mobile applications, (ii) equipment and materials response to liquid hydrogen (LH_2) transfer and incident roots, as well as (iii) releases, combustion, and explosion phenomena both outdoor and in enclosure spaces will be pursued. For the first time, a study on the frequency of failure of LH_2 transferring equipment will be carried out by exploiting the internal databases of some of the consortium partners which contain valuable information collected in the last decades. Therefore, both probabilities and consequences of failure will be investigated in ELVHYS for the selected accident scenarios. In this fashion, critical inputs can be provided for the development of recommendations, codes, and international standards by creating safe and optimized procedures and guidelines for cryogenic hydrogen transferring technologies.

The University of Bergen (UiB) and University of Stavanger (UiS) are involved in various projects that explore the Strength of Knowledge (SoK) in risk assessment for hydrogen systems, including *SH2IFT-2* (mentioned above), *Norwegian Centre for Hydrogen Research* (HyValue), and *Hydrogen as an Energy Carrier in society: Risk Picture, Risk Awareness and Public Acceptance* (HySociety). UiB is also involved in other projects that address various aspects of the SoK related to large-scale implementation of hydrogen: *Safe Hydrogen Implementation: Pre-normative research for Ships* (SH2IPS) and *Large-Scale Offshore Hydrogen Storage for Green Energy Transition* (Hy4GET). Up to now [18], the research activities have focused on the ‘crude direct grading approach’ proposed by Aven [19]. However, future work includes a critical analysis and development of alternative SoK frameworks for hydrogen.

Research activities in the SH2IFT-2 and SH2IPS projects also include benchmark studies where researchers and safety/risk engineers will be invited to take part in comparative risk assessments for hypothetical systems (e.g., bunkering operations for compressed or liquified hydrogen). SH2IFT-2 also includes large-scale experiments that will be combined with blind-prediction benchmark studies for consequence models, as well as users of such models. In a somewhat longer perspective, UiB and UiS will organize a blind-prediction benchmark study in connection with the large-scale hydrogen explosions experiments planned in the HyValue project.

E.3 Developing advanced QRA methods and prognostics and health monitoring techniques

Activities under this topic focus on developing new, cutting-edge methods from reliability engineering and risk assessment research that could be integrated with current QRA methods or replace QRA methods to advance the technical basis of conducting QRAs for hydrogen safety. Data-driven techniques of prognostics and health management (PHM) could provide new damage diagnosis and health-state prognosis tools that advance the state of the art in hydrogen safety while also streamlining maintenance activities [1]. The combination of leak rate quantification research, PHM, and QRA can lead to better informed models enabling data-based decisions to be made for hydrogen system safety improvements [11].

Exploring the connection between QRA and PHM is a key goal of UMD’s SIPPRA project on modernizing risk assessment through *Systematic Integration of PHM and Probabilistic Risk Assessment* (PRA or QRA), funded by the U.S. National Science Foundation (NSF). UMD developed the SIPPRA framework to connect PHM and QRA in 2020 [20] and demonstrated its mathematical methods for a series of case studies, including dynamic risk monitoring of an oil and gas vapor recovery unit [21]. Recent work has developed a hydrogen system implementation of SIPPRA by connecting machine learning models, causal models, and data and models from HyRAM to assess risks associated with using natural gas pipelines to transport hydrogen [22]. UMD is actively seeking partners with data suitable to develop dynamic risk monitoring tools for other hydrogen technologies.

UMD and NREL have explored the possibility of using PHM techniques together with sensor-based monitoring to enable anomaly detection and fault diagnostics as well as prognostics for liquid hydrogen storage on-site at fueling stations within hydrogen safety, reliability, and risk applications [23]. Predictive modeling of failures could improve safety requirements such as setback distances at liquid hydrogen fueling sites or could pave the way for risk-informed preventative maintenance activities to be used at those facilities.

NTNU and its partners in the SUSHy Project are also pursuing advanced methods through the connection of traditional QRA to digital twins and dynamic simulation techniques. Coming back to the case of HREP hydrogen fueling stations, designed protection and emergency response systems typically fall within one of the following categories [24, 25]: detectors and alarms for slight hydrogen leaks, automatic shutdown systems to close the hydrogen valve quickly, emergency exhaust systems, inert gas nitrogen introduction systems, cooling systems, fire-extinguishing systems (e.g., water spraying) and anti-explosion walls. A novel, probabilistic digital twin model at the system level is currently under development, taking into consideration scenarios identified in another work package of the SUSHy Project (see Section E2 above). The aim is to analyze the effectiveness and performance of the aforementioned safety systems under the uncertainties involved in given scenarios. Answering the calls of current research [26, 27], this work is aimed at combining more conventional risk assessment methodologies (as mentioned in Section E2) with methods from safety barrier engineering, model-based systems engineering and intelligent digital approaches. Multi-phase Markov Chains or hybrid (i.e., deterministic and stochastic) Petri-Net techniques will be used to simulate dynamic behaviors of the production and safety systems, as well as the fluctuations in renewable power generation. New algorithms will be developed and verified to achieve (near) real-time risk assessment. In addition, a block-diagram approach will be proposed to evaluate the effectiveness of safety-critical equipment, and optimize their specifications, placement, and operational regime for mitigating domino effects, such as jet fires.

4. POTENTIAL CASE STUDIES

E4 Hydrogen system case studies for hydrogen system safety analysis

The development of case studies is the focus of topic E4, which will develop all aspects of QRAs for real-world hydrogen systems and equipment. This includes identifying hydrogen system failure scenarios, calculating scenario probabilities, and assessing scenario consequences in an integrated fashion. The results will be used to evaluate novel hydrogen technologies. The identification and development of case studies is one of the next steps for Subtask E and will be conducted in coordination with other subtasks (e.g., [28]). In Subtask E, the emphasis is on insights into the safe operation of compressed gaseous and liquid hydrogen energy systems involving mechanical and process equipment or vehicles. Anticipated applications include equipment and vehicles in confined environments such as hydrogen equipment enclosures, repair facilities, underground parking structures, tunnels, and related deployments. Examples of hydrogen systems of near-term interest include electrolyzers, compressors, storage systems, fueling stations, and vehicles.

Within the first year of Subtask E activities, members are considering developing a wide range of case studies that cover various hydrogen technologies, applications, and countries. A large number of case studies have been suggested by participants. Further discussion of most of the potential case studies is deferred until a future paper.

Completing a full analysis implies the need for details of hydrogen systems and equipment to allow for this. As an example, one case study under consideration is the ongoing work by NREL and AVT on “Ventilation Study of Confined Hydrogen Releases from Failed Components with Characterized Leak Parameters.” This work includes three focus areas:

1. CFD modeling of characterized leaks under various ventilation conditions and leak directions in mechanically ventilated enclosures.

2. Integration of the CFD results for the characterized leaks into HyRAM to estimate potential overpressures for consecutive risk assessment.
3. Dissemination of the recommendations for hydrogen equipment enclosures to relevant standard development bodies.

A sample of the modeled enclosure is shown in Figure 2. AVT and NREL have completed CFD and HyRAM simulations of defined releases in this enclosure [29]. The comparison includes leak sizes recommended by IEC 60079-10-1 and leaks identified of the failed component in the field as well as the expanded leak size during testing at NREL. A modified code that enables HyRAM to directly imports CFD results into its layer model was also developed for this work; this enables more fidelity in representing the influence of the geometry, leak direction, and ventilation on the accumulation of hydrogen. Early results are discussed in [29] and full results will be available by the end of 2023.

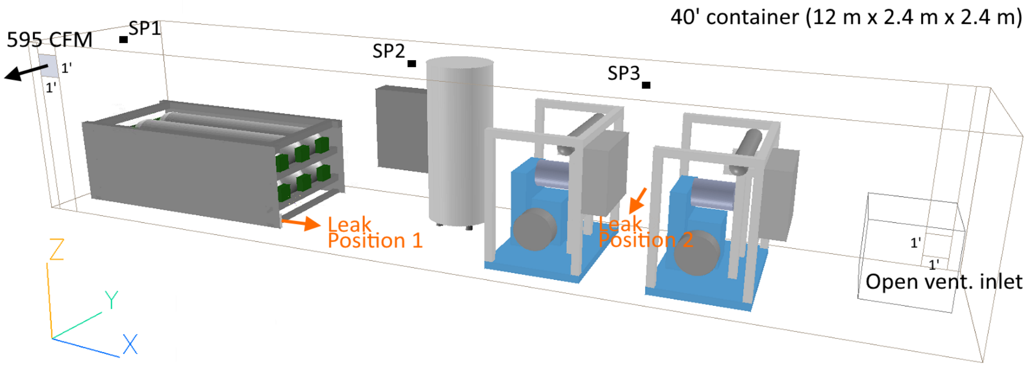

Figure 2: Equipment enclosure geometry for a potential case study [28]

This case study could be extended by using the QRA methods such as those discussed in E2. Release probabilities could be taken from the HyCReD data or other data sources discussed in E1. The analysis could be expanded to assess the effect of a wide variety of mitigations, such as prevention measures including gas detection combined with improved ventilation in buildings/rooms, improved control of ignition sources, improved component reliability, system redesign, improved maintenance, and more.

5. CONCLUSION

Maintaining a record of safe hydrogen deployments is critical to the widespread adoption of hydrogen technologies, and international sharing of knowledge is of fundamental importance to ensuring safety. To this end, the IEA Hydrogen Task 43 Subtask E on Hydrogen System Safety is focused on creating, disseminating, and exchanging knowledge to address technical gaps in the safety, risk, and reliability analysis of hydrogen systems. The subtask is structured around four topics: E1 - Reliability data collection and curation, E2 - Improvements to current QRA tools, E3 - Developing advanced QRA and prognostics methods, and E4 - Developing hydrogen system case studies for hydrogen system safety analysis. The emphasis is on insights for the safe operation of compressed gaseous and liquid hydrogen energy systems involving mechanical and process equipment or vehicles. Anticipated applications include equipment and vehicles in confined environments such as hydrogen equipment enclosures, repair facilities, underground parking structures, and related deployments. Subtask E is designed to create scientific outputs that can support the development of requirements, codes, standards, and best practice recommendations for the safe operation of hydrogen systems. The Subtask E results will be fed into Subtask F to create guidance to the industry and input to requirements, codes, standards, and best practices.

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