A toolkit for integrated deterministic and probabilistic risk assessment for hydrogen infrastructure

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Abstract: There has been increasing interest in using Quantitative Risk Assessment [QRA] to help improve the safety of hydrogen infrastructure and applications. Hydrogen infrastructure for transportation (e.g. fueling fuel cell vehicles) or stationary (e.g. back-up power) applications is a relatively new area for application of QRA vs. traditional industrial production and use, and as a result there are few tools designed to enable QRA for this emerging sector.

There are few existing QRA tools containing models that have been developed and validated for use in small-scale hydrogen applications. However, in the past several years, there has been significant progress in developing and validating deterministic physical and engineering models for hydrogen dispersion, ignition, and flame behavior. In parallel, there has been progress in developing defensible probabilistic models for the occurrence of events such as hydrogen release and ignition. While models and data are available, using this information is difficult due to a lack of readily available tools for integrating deterministic and probabilistic components into a single analysis framework. This paper discusses the first steps in building an integrated toolkit for performing QRA on hydrogen transportation technologies and suggests directions for extending the toolkit.

Keywords: hydrogen; integrated deterministic and probabilistic; codes and standards; software; QRA;

1. INTRODUCTION

Early market hydrogen fuel cell installations have set a precedent for safe use of hydrogen. As the hydrogen industry shifts toward market deployment and commercialization, safety remains a top priority. In North America, hydrogen infrastructure must meet all applicable codes and standards to demonstrate that they are safe, reliable, and compatible.

Considerations of regulations, codes, and standards (RCS) for use of hydrogen as a transportation fuel are influenced by industrial gas, oil and gas and nuclear power industries. The RCS requirements used in these traditional industrial applications are generally conservative and often barriers to the further promulgation of hydrogen fueling infrastructure. To address these limitations, and to enhance the scientific basis for codes and standards, there has been a push toward using risk information to develop and revise hydrogen-specific standards such as NFPA 2: Hydrogen Technologies Code. During the previous code cycle, various parts of NFPA 2 have been revised using a combination of deterministic and probabilistic analyses. QRA has been performed to address separation distances in the 2011 revision to NFPA 2 [1], and to address size limits of fueling rooms in the 2014 code revisions [2]. Similar work is being planned during the upcoming revision cycle of the Canadian Hydrogen Installation Code (CHIC) within the 2014-15 timeframe.

While general QRA methods are applicable to hydrogen systems, more widespread use of QRA for code revisions is limited due to significant gaps in current data, models, and tools available for applying QRA on hydrogen systems. These gaps have been discussed in the references [2], [3], [4], [5]. Major gaps include the lack of hydrogen-specific data for use in scenario quantification (especially release probabilities) and the lack of physics-based, hydrogen-specific models (for use in

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deriving ignition probabilities, and for consequence modeling), and inadequate handling of uncertainty. Several international research teams are actively working to address many of these gaps through data collection, experiments, and analyses.

In June 2013, Sandia and HySafe organized an expert workshop to identify limitations of existing QRA tools [5]. Additional gaps identified during the workshop include oversimplified assumptions regarding leak duration and ignition timing, and a lack of tools for performing QRA with hydrogen-specific models and data.

The results of the workshop showed that use of QRA for hydrogen applications currently suffers from inefficiency, requiring multiple experts and a variety of disparate modeling techniques. These deficiencies prevent the code development committees from self-sufficient operations, as they require multiple experts to consolidate and operate the relevant probabilistic and physical models. The deficiencies also affect the industry as they struggle to design systems compliant with the codes, suggest revisions to the code and apply for variances to codes necessitated by site-specific constraints.

Sandia and HySafe are working to build simplified toolkits to facilitate the use of QRA within the hydrogen fuel cell industry. This paper presents progress on those activities. Section 2 discusses the purpose, basic concept, objectives and targeted audiences for QRA tools applied to hydrogen. Section 3 discusses the underlying hydrogen-specific QRA methodology, which integrates available probabilistic and deterministic models into a single approach. Section 3 also discusses how this methodology is implemented in Sandia's HyRAM (Hydrogen Risk Assessment Models) toolkit, which is intended to support development of hydrogen codes and standards such as NFPA 2. Section 4 discusses the HyRAM interface design, and Section 5 presents the next steps for development of hydrogen-specific QRA tools.

2 TOOLKIT NEED

2.1 Purpose

From the hydrogen safety research community perspective, one of the key tasks of scientific work is to translate fundamental scientific findings into practical formulas, which are easily applied in daily work. While Computational Fluid Dynamics (CFD) codes produce high resolution results for complex physical phenomena, the substantial financial and computational resources required for CFD make it unusable for daily safety decisions. For many safety decisions or for analyses with large numbers of relevant variables (i.e., QRA), validated simplified models, correlations, and statistics data can be used to provide robust results with significantly fewer resources than required by simulations.

The goal of this work is to integrate these simplified pieces into a software toolkit that can be used to assess the hazards and risk in scenarios associated with certain hydrogen system configurations, in a timely manner. Significant and ongoing international efforts, initiated under the auspices of the US DOE, the IEA HIA Tasks 19/31 on hydrogen safety and HySafe, produce various first order models, statistical models, empirical correlations and criteria for the myriad physical and engineering processes relevant to understanding the hazards associated with hydrogen systems. The resulting toolkit will provide practical, efficient access to state-of-the-art models and data required to perform risk assessments of hydrogen systems. In particular subject matter experts, who cannot afford their own safety research or expensive numerical simulations, will benefit from this unique resource. At the same time, the toolkit can serve as a reference basis for the development of risk-informed RCS

2.2 Basic Concept

The primary objective is to develop a library of modern hazard assessment tools that contains best-available models and data relevant to understanding and quantifying risk in hydrogen fuel cell infrastructure. The toolkit must:

- Contain the latest available data and models (ideally, validated for hydrogen infrastructure use) relevant to quantifying the probability of progression various hazard scenarios;
- Contain the latest available data and models (ideally, validated for hydrogen infrastructure use) relevant to prediction of physical properties of hydrogen releases and ignition events, and the consequences of those events;
- Contain risk metrics the represent observable quantities (e.g., physical parameters, losses, number of fatalities) relevant to decision making for safety, codes, and standards
- Facility relative risk comparison, sensitivity analysis, and treatment of uncertainty;
- Be built in a modular configuration;
- Contain user-friendly, graphical interfaces;
- Provide default models, values and assumptions, and provide transparency about those defaults; furthermore, it must allow modification of these defaults to reflect different systems and new knowledge.

The toolkit has two stakeholder audiences: *users* and *developers* [5]. The *users* group includes organizations and analysts interested in developing codes and standards, designing and permitting stations, justifying code variances, etc. The *developers* group includes researchers and agencies who focus on development and validation of the underlying models and data.

As safety is a public concern and a big part of relevant scientific work is funded by public agencies, the toolkit would ideally be an open and free software system, that is well documented and quality assured in a cooperative manner. Ideally, the tools shall be maintained by the hydrogen safety research community itself, after an initial framework is developed by public agencies such as the US DOE. A potential custodian of an international toolkit might be HySafe.

A typical case will consist of a user-defined scenario specified by the inventory or hydrogen flow, geometrical settings (e.g., confinement and/or congestion), system parameters, mitigation measures, up to a maximum release size. For a statistical analysis, including treatment of uncertainty, any of these scenario properties could also be defined by a probability distribution instead. Then the user will select among appropriate models for analysing the scenario. The input required by the selected tool will be input by the associated tool interface. If any of the input parameters lie outside the validity range of the models, an appropriate warning will be displayed for the user.

Each module will have a defined documented set of input parameters and a set of output or result parameters. Each module shall be described in detail, with a defined valid range of input parameters. Literature support and experimental and computational validation exercises relevant to each module should be documented, along with the valid range of the model and key underlying assumptions.

With all requirements defined so far, multiple implementations can be envisaged. Independent custodians of the toolkit could facilitate development and use for the different communities. Many configurations or arrangements of custodianship are possible and require international partnership. In the current approach, Sandia is developing a toolkit targeted toward US DOE domestic stakeholders (such as the NFPA 2 code committee or state fire marshals). In parallel, HySafe is coordinating the international community to “crowd-source” efforts to develop and host an open-source toolkit.

The Sandia version is being developed in C# with an underlying MVC (Model View Controller) framework to enable development of multiple different user views on top of the same underlying models. Sandia is currently pursuing a .NET software framework with a planned Windows and HTML interfaces for codes and standards users. For the international version being developed by HySafe, a WEB2.0 kind of implementation is envisaged; a system which allows for immediate testing and on-the-fly editing of the tools is the Smalltalk dialect Squeak based dynamic web development framework Seaside.

3. QRA APPROACH

The methodology used in Sandia's HyRAM toolkit starts with the hydrogen-specific QRA approach documented in [2]. The approach uses a combination of probabilistic and deterministic models to evaluate the expected fatal accident rate for workers in a warehouse with an indoor hydrogen fuel dispenser. The methodology uses traditional probabilistic approaches to assess the likelihood of various hydrogen release and ignition scenarios, which can lead to thermal and overpressure hazards. Several types of deterministic models are used together to characterize the physical effects of the hazards. Information from the physical effect models is passed into probit functions used to calculate consequences in terms of number of fatalities.

3.1 Risk Metrics

Currently, the methodology focuses on calculating fatality risk. The HyRAM toolkit includes three well-known fatality risk metrics:

- FAR (Fatal Accident Rate) – the expected number of fatalities per 100million exposed hours
- AIR (Average Individual Risk) – the expected number of fatalities per exposed individual
- PLL (Potential Loss of Life) – the expected number of fatalities per system-year.

In addition to the fatality risk metrics, the code also outputs various metrics, which may be relevant to codes and standards users:

- Expected number of hydrogen releases per system-year (unignited and ignited cases)
- Expected number of jet fires per system-year (immediate ignition cases)
- Expected number of deflagrations/explosions per system-year (delayed ignition cases)

3.2 Hazards

The primary hazards related to the use of hydrogen are the release and subsequent ignition of hydrogen. The two main hazards associated with releases of hydrogen are exposure to thermal radiation from jet fires and exposure to overpressures from explosions. Both of these hazards can affect people, property, structures, and the environment directly or indirectly.

Two other hydrogen-related hazards are not included in the approach from [2]: asphyxiation and projectile damage. Hydrogen can cause oxygen displacement, which can lead to asphyxiation. However, since hydrogen is highly buoyant and diffusive, asphyxiation is likely only a concern in extremely small, well-sealed spaces. High-pressure gases escaping from a ruptured containment vessel can propel debris or projectiles at high velocity. However, due to the continuous improvement of gas storage cylinder technology (e.g., leak-before-rupture failure mechanisms, passive protection measures like temperature-actuated pressure relief devices), it is assumed that risk from fires significantly dominates risk from debris. As a result, the risk of projectiles is not modeled in the current framework. Future modules should be designed to address these hazards, or quantitative analyses should be conducted to ensure that these hazards negligibly contribution to risk for all use cases.

3.3 Accident Scenario Models

A jet fire is assumed to result from the immediate ignition of a hydrogen release, while delayed ignition events result in explosions (e.g., deflagrations or detonations). These two hazards can be represented in an Event Sequence Diagram (ESD) model, as shown in Figure 1.

The initiating event for all scenarios is a release of hydrogen gas from a hydrogen system (e.g., damaged piping or a lose fitting or valve on a storage tank, compressor or dispenser,). Hydrogen releases from the dispenser can occur through one of several mechanisms:

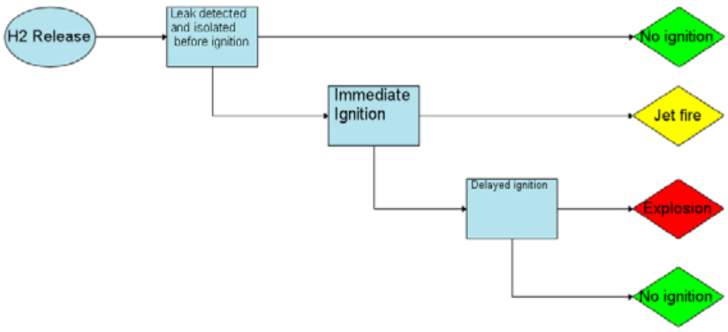
- External leaks from individual components, or separation of an individual component
- Shutdown failures
- Accidents

Release characteristics vary widely, and different sized releases are associated with different consequences, and in some cases with different causes. The approach assumes one ESD for each of five releases sizes, based on release areas equal to specific percentages of the pipe cross-sectional flow area: 0.01%, 0.1%, 1%, 10%, 100%. In the HyRAM toolkit, users input the pipe outer diameter and wall thickness, and the toolkit calculates pipe flow area and release size. In future versions, release size may be sampled from a distribution instead of assigned by the algorithm.

3.2.1 Accident Scenario Quantification

Quantification of 100% releases is based on a combined Fault Tree (FT) and parts count approach; release frequencies for the other four release sizes are based solely on the parts count approach. To analyze a system, users input parts counts for each of the nine component types: compressors, tanks, filters, flanges, hoses, joints, pipes, valves, and instruments.

Figure 1: Event Sequence Diagram for scenarios resulting from hydrogen releases.



The parts count approach uses frequency data generated from a Bayesian combination of hydrogen-specific data with data from similar industries, provided in [6]. Each combination of component type and leak size is associated with a lognormal distribution for frequency of leaks (per year). Quantification is achieved by multiplying the number of components by component-specific leak frequencies.

A FT approach is used to incorporate root causes of shutdown failure and accidents. The quantification of 100% releases is achieved by adding the frequencies from the part counts to the release probabilities obtained by multiplying annual system demands by the results of the FT. Users manually enter number of system demands. Currently, cut-sets associated with the system FT must be hard-coded into HyRAM. Component failure probabilities (per demand) for the basic events in the FT were assembled from generic data from non-hydrogen industries, documented in [2]; each of these failures events is associated with either a beta distribution or an expected value.

Hydrogen ignition probabilities used in the ESD were developed by Tchouvelev within the Canadian Hydrogen Safety Program [7]. This approach uses a look-up table to assign mean probability of immediate and delayed ignition as a function of hydrogen release rate. The hydrogen release rate used to assign ignition probabilities is discussed in Section 3.4.1. The leak detection and mitigation event in the ESD is quantified using a point estimate value documented in [2].

In the current HyRAM toolkit, calculations are performed with mean values of the associated probability distributions. The scenario module outputs a vector of expected annual frequencies of jet fires and of explosions resulting for each of the five release sizes.

3.4 Physical Effects Models

Physical effects models are used to characterize the magnitude of hazards associated with ignited hydrogen releases. The primary physical effects of ignited gaseous hydrogen releases are fire effects (impinging flames, temperature, heat flux) and explosion effects such as pressure and impulse waves. The dominant damage mechanism from jet flames is heat flux, and the dominant damage mechanism from explosions is overpressure.

Characterizing physical effects requires modeling a series of aspects of hydrogen behavior: release behavior, flame initiation, flame sustainment, radiation patterns and overpressures. In HyRAM, we use a combination of available first-order deterministic behaviors models and CFD models.

3.4.1 Hydrogen Release Characteristics

The first step in characterizing consequences is to characterize the release of hydrogen and the extent of the flammable envelope. Thermodynamic parameters of releases from high-pressure hydrogen systems can be estimated using notional nozzle models. Papanikolaou et al [9] compare five notional nozzle models for hydrogen jets, and found that the best accuracy was obtained by using either the Schefer et al. [10] or the Birch et al. [11] models. Both models implement conservation of mass and momentum, but the two models implement different equations of state. Birch uses the Ideal gas law, whereas Schefer implements the Abel-Noble equation of state for non-ideal gases.

HyRAM incorporates the Schefer notional nozzle model because high-pressure hydrogen releases exhibit non-ideal gas behavior. User input consists of system temperature and pressure, and ambient temperature and pressure. For each of the five release sizes, the nozzle model outputs key thermodynamic parameters: hydrogen mass flow rate, effective gas temperature at the exit, effective gas density at the exit, effective release velocity, effective leak area and diameter at the exit, effective Mach number, and gas pressure, temperature and density at the nozzle throat.

3.4.2 Hydrogen jet flame effects

Releases from high-pressure hydrogen systems that are ignited immediately produce momentum driven jet flames. Houf and Schefer [12] developed and validated a first-order model for predicting the radiative heat flux and the flammability envelope of a hydrogen jet flame; this model has been used to provide the basis for several parameters specified in NFPA2.

The HyRAM code incorporates the Houf & Schefer model, which is used to calculate the heat flux at a given axial and radial distance from a hydrogen jet flame. This module uses the thermodynamic parameters calculated by the notional nozzle model as input conditions. User input consists of information about the axial and radial positions of interest.

Since the focus of the current approach is on human harm, the positions of interest are places where people are located relative to the flame. In the current version of HyRAM, users input the number of potentially exposed persons (e.g., number of persons in the warehouse or near the facility) and the length and width of the facility (measured from the system). HyRAM includes a module that generates a random position for each person by sampling either a uniform distribution or a normal distribution. The axial and radial position of each person is fed into the Houf and Schefer model. The output is a matrix containing a heat flux value for each person, for each release size.

3.4.3 Overpressure effects

The dominant damage mechanism from explosions is overpressure. Since first-order model for predicting overpressure and impulse effects for QRA purposes are still being developed, the HyRAM toolkit requires user input from the results of simulations to enable the QRA calculations. CFD codes such as FLACS, FUEGO, and FDS have been used to simulate overpressure and impulse effects, and have been validated for aspects of hydrogen behavior [21], [22].

3.5 Harm (Fatality) Models

The results of physical effects evaluations must be translated into a probability of causing damage to an individual, component, or structure for use in a QRA. Probit models are used to establish the probability of injury or fatality for a given exposure. LaChance et al. [13] provides an overview of probit models for thermal exposures and for overpressure exposures, and provides recommendations regarding the applicability of the models to hydrogen hazard scenarios. HyRAM incorporates the four probit models for thermal fatalities: the Eisenberg model [14], the Tsao & Perry model [15], the TNO model [16], and the Lees model [17]. HyRAM also incorporates several overpressure models: lung hemorrhage fatality models by Eisenberg [18] and by HSE [19], as well as the TNO models [20] for head impact fatalities, for structural collapse, and for debris impact fatalities.

For thermal exposures the consequences to the exposed person are a function of radiative heat flux and exposure time. The thermal probit module uses the heat flux vector from the jet flame module. User input consists of a thermal exposure time for the population. The output is a matrix of thermal fatality probabilities; this vector is summed over the population to provide a vector the expected number of fatalities from thermal exposures for each release size.

For overpressure exposures, the consequences to the exposed person are a function of peak overpressure; this value is obtained from the overpressure effects calculations The TNO probit models also require impulse values or projectile fragment mass and velocity. Impulse values are obtained from the overpressure effects calculations. If a projectile model is selected, users must manually enter projectile fragment mass and velocity. As was done for the thermal fatalities, the expected number of fatalities from a given release size was calculated by summing the probability of fatality over the entire exposed population.

4. SANDIA'S HyRAM PLATFORM

4.1 User interfaces

The HyRAM toolkit contains two user-interfaces – one interface designed to facilitate performance-based permitting of hydrogen stations via the alternate design option provided by NFPA2 (the pilot user group), and a second for end-to-end QRA analysis using the approach from [2]. A planned third interface will allow stand-alone implementation of any of the deterministic consequence models.

The interfaces in HyRAM are designed to facilitate user activities such as comparison among various options (e.g., RCS requirements, design tradeoffs) and also comparison with other industries. Because of the focus on relative risk comparison and fast-running calculations, simplified models are be used in lieu of resource intensive simulations or CFD models. While the users have a strong need for defensible underlying physics models in the toolkit, they do not necessarily intend to manipulate the parameters of those underlying models. The development and selection of underlying model parameters fall under the purview of the developer community.

4.2 Code structure

The HyRAM toolkit is being developed in the MVC (Model-View-Controller) framework. The use of MVC enables a single underlying model to be associated with multiple user views. This flexible framework permits development of multiple user interfaces to meet the needs of different groups of users. The target platform is the .NET environment, with planned extension to an HTML interface after completion of the initial .NET interfaces. Both interfaces will contain user views targeted at QRA analysts and other user views targeted for NFPA2 users. The algorithm described in Section 3 has been modularized, as pictured in the flowchart in Figure 2. User input is divided into three categories: system component counts, system design parameters, and facility parameters (see Table 1). Users must also select the probit function to be used in calculating thermal and overpressure fatalities, using the options described in Section 3.5. Currently users must also enter peak overpressure and impulse for each release size. The default ESDs and FT from [2] are programmed as the initial scenarios in the toolkit.

HyRAM contains the frequency data generated from a Bayesian combination of hydrogen-specific data with data from similar industries, as provided in [6]. Each combination of component type and leak size is associated with a lognormal distribution for frequency of leaks (per year). HyRAM also contains generic values for component failure probabilities (per demand) for the basic events documented in [2]. Additionally, the toolkit contains physical constants and parameters relevant to hydrogen gas behavior modeling, including molecular weight, flammability limits, heat of combustion, and others. Data is stored internally in SI units, and the toolkit contains modules to enable conversion to English units.

Figure 2: Flowchart of modules contained in the HyRAM toolkit

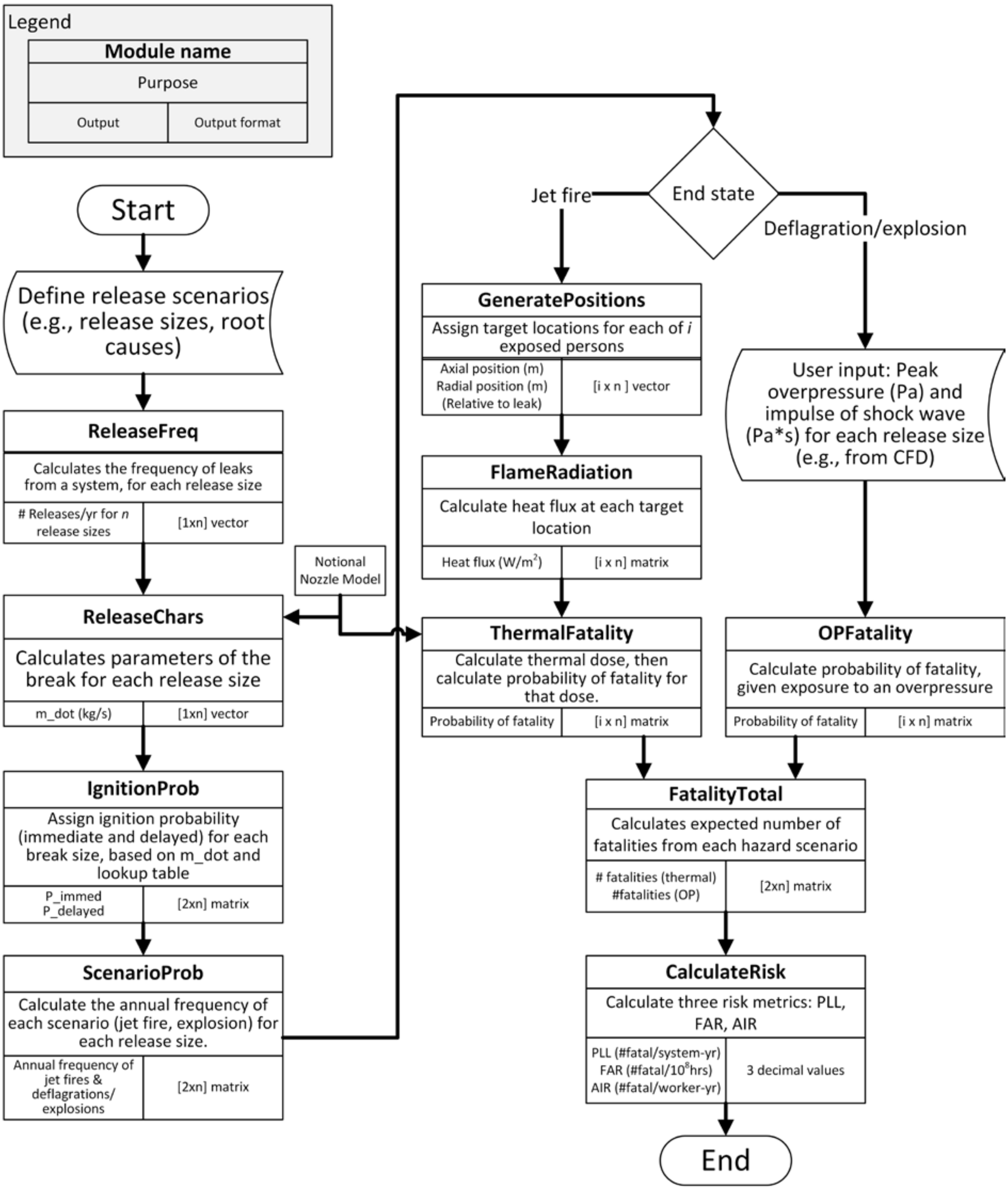


Table 1: Required user input for the HyRAM toolkit

System Component counts	System design parameters
- Compressors (#) - Cylinders (#) - Valves (#) - Instruments (#) - Joints (#) - Hoses (#) - Pipes (m) - Filters (#) - Flanges (#)	- Pipe outer diameter & wall thickness - Internal temperature, pressure - Number of demands (annual) Facility parameters - Facility temperature, pressure - Dimensions: length, width, height - Population: number of persons, locations, exposed (working) hours

5. NEXT STEPS

The HyRAM toolkit is in an early stage of development, and there are many features that must be added or improved to better enable the use of QRA. Filling these gaps requires a broad range of expertise and significant effort from the international hydrogen community. The proposed toolkit provides a framework for unifying the resulting science and engineering models into a tool to support RCS development. There are a number of areas for extension of the toolkit; some require developing or expanding science and engineering models, and others require the implementation of existing models in a compatible computational framework. Some key areas for expansion are:

- **Inclusion of additional hazards.** In previous work, it has been assumed that the risk contribution from fire and overpressure effects will render the risk contribution of debris and asphyxiation to be negligible. However, performance-based design scenarios require consideration of pressure vessel burst scenarios and toxic releases, in addition to fire and explosion scenarios. Future work will identify candidate models suitable for addressing these hazards, which may then be implemented in the HyRAM system.

- **Expanding treatment of uncertainty.** Assumptions about the timing of ignition and duration of exposures both significantly impact the calculated risk results. Future versions of the toolkit should be expanded to include dynamic risk assessment methods or sampling techniques to address uncertainty in timing and duration. In the current toolkit, calculations are limited to use of mean values from the probability distributions for leaks and component failures. Future versions of the toolkit will contain modules that enable sampling over the full distribution range.

- **Development of graphical interface for ESDs and FTs.** Future versions will include a graphical interface that enables users to modify the ESD/FT models and the probabilities associated with basic events, etc.

- **Inclusion of additional risk metrics.** The current toolkit focuses on calculating fatality risk. However, codes and standards users have also expressed interest in estimating risks that can be expressed in terms of cost. Future versions may also include features that enable plotting QRA results alongside various externally defined risk metrics or risk acceptance criteria.

- **Inclusion of additional physics models.** The current toolkit lacks simplified models for predicting overpressures from hydrogen deflagration, detonation events, as well as physical behavior of liquid hydrogen releases. Sandia has developed first-order models relevant to modeling the accumulation of hydrogen in delayed ignition events, and has also identified first order models for overpressure prediction. These models will be incorporated into the next version.

- **Increasing fidelity of included physics models.** Ruggles and Ekoto [8] performed a comparative study on various notional nozzle approaches and conducted experimental work comparing notional nozzle model predictions with measured hydrogen properties in free jets. They suggest a series of improvements to better reflect release thermodynamics, such as near-field jet entrainment. Similarly, the free jet assumption may also need to be adjusted, since many hydrogen leaks occur in close proximity to surfaces and barriers. Benard and Tchouvelev [23] have performed extensive studies of surface effects on hydrogen and methane jets and developed engineering correlations that take into account release pressure, orifice and proximity to surfaces for both horizontal and vertical jets. These and other physics-based model improvements are further discussed in [4].

In addition to these next steps for developing the toolkits, a more general, and omnipresent concern, is development and validation of models and datasets for use in the toolkit. The inclusion of meaningful, representative data in the toolkit is of critical importance to successful, defensible implementation for QRA. Developers must collaborate with data-collection organizations to ensure that data are of sufficient fidelity to be used in the toolkit. Industry groups may be able to facilitate data availability by collecting and sanitizing data for use in the toolkit. Furthermore, science-based models must be continually developed, validated, and integrated into the toolkit, to reduce uncertainty and to ensure that RCS decisions are based on defensible, accurate information.

6. CONCLUSION

QRA is an important tool for maintaining the safety and the commercial viability of the hydrogen industry, and is thus expected to play an increasing role as hydrogen technology shifts toward market deployment. Furthermore, QRA offers a means for using the best science and engineering models to develop codes and standards, as well as to facilitate the design and permitting process for hydrogen fueling stations. While there has been progress in developing defensible probabilistic and deterministic models for hydrogen systems over the past decade, use of QRA is limited due to lack of readily available tools for integrating and implementing these models for use by the hydrogen safety community.

Sandia and HySafe are working to build simplified toolkits to facilitate the use of QRA within the hydrogen fuel cell industry. The toolkit methodology integrates relevant probabilistic and deterministic physics models into a single analysis framework. The toolkits are intended to provide a practical, open access to the state-of-the-art required for hydrogen risk assessments of the hydrogen and fuel cell industry. In particular, industry experts, including codes and standards developers and station designers, who need fast running, high-level insights rather than expensive and resource-intensive numerical simulations, will benefit from this unique resource. At the same time, the toolkit may serve as a reference basis for the development of risk-informed standards and regulations, such as NFPA2. The HyRAM toolkit as well as the tools being developed by HySafe provide a framework for bringing together the expertise of the international hydrogen safety research community and putting it in the hands of the decision makers who ensure the safety of the hydrogen industry.

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References

[1] J LaChance. "*Risk-informed separation distances for hydrogen refueling stations*." International Journal of Hydrogen Energy, 34, pp. 5838-5845 (2009).

[2] KM Groth, JL LaChance, & AP Harris. *Early-Stage Quantitative Risk Assessment to Support Development of Codes and Standard Requirements for Indoor Fueling of Hydrogen Vehicles.* SAND2012-10150, Sandia National Laboratories, (2012).

[3] HJ Pasman. "*Challenges to improve confidence level of risk assessment of hydrogen technologies*" International Journal of Hydrogen Energy, 36, 2407-2413 (2011).

[4] A Kotchourko et al. "*State of the art and research priorities in hydrogen safety*" (Draft report) European Commission Joint Research Centre, (2014).

[5] K Groth & A Harris. "*Hydrogen Quantitative Risk Assessment Workshop Proceedings*." SAND2013-7888, Sandia National Laboratories (2013).

[6] J LaChance et al. "*Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards.*" SAND2009-0874, 2009.

[7] A Tchouvelev. "*Quantitative Risk Comparison of Hydrogen and CNG Refueling Options*." Canadian Hydrogen Safety Program Presentation at IEA HIA Task 19 Meeting, (2006).

[8] AJ Ruggles, & IW Ekoto, "*Ignitability and mixing of underexpanded hydrogen jets*." International Journal of Hydrogen Energy, 37, pp. 17549-17560 (2012).

[9] E Papanikolaou, D Baraldi, M Kuznetsov, A Venetsanos, "*Evaluation of notional nozzle approaches for CFD simulations of free-shear under-expanded hydrogen jets*", International Journal of Hydrogen Energy, 37, pp. 18563-18574 (2012).

[10] RW Schefer, et al. "*Characterization of high-pressure, underexpanded hydrogen-jet flames*", International Journal of Hydrogen Energy, 32, 2081 (Aug, 2007).

[11] AD Birch, DJ Hughes, F Swaffield. "*Velocity decay of high pressure jets*." Combustion Science and Technology 52, 161-171 (1987).

[12] W Houf & R Schefer. "*Analytical and experimental investigation of small-scale unintended releases of hydrogen*." International Journal of Hydrogen Energy, Elsevier, 2008, 33, 1435-1444

[13] J LaChance, A Tchouvelev, & A Engebo. "*Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure*." International Journal of Hydrogen Energy, 2011, 36, 2381-2388

[14] NA Eisenberg, CJ Lynch, & RJ Breeding. "*Vulnerability model. A simulation system for assessing damage resulting from marine spills.*" SA/A-015 245, U. S. Coast Guard, (1975).

[15] CK Tsao & WW Perry. "*Modifications to the vulnerability model: a simulation system for assessing damage resulting from marine spills.*" Report ADA 075 231 US Coast Guard; (1979).

[16] G Opschoor, ROM van Loo & HJ Pasman. "*Methods for calculation of damage resulting from physical effects of the accidental release of dangerous materials*." International Conference on Hazard Identification and Risk analysis, Human Factors, and Human Reliability in Process Safety. Orlando, Florida; January (1992).

[17] FP Lees. "*The assessment of major hazards: a model for fatal injury from burns*." Transactions of the Institution of Chemical Engineers;72(Part B):127e34 (1994).

[18] Center for chemical process safety. "*Guidelines for chemical process quantitative risk analysis.*" American Institute of Chemical Engineers, (2000).

[19] UK Health & Safety Executive. "*Major hazard aspects of the transport of dangerous substances.*" (1991).

[20] "*Methods for the determination of possible damage*." In: CPR 16E. The Netherlands Organization of Applied Scientific Research; (1989).

[21] P Middha, OR Hansen, J Grune, J & A Kotchourko. "*CFD calculations of gas leak dispersion and subsequent gas explosions: Validation against ignited impinging hydrogen jet experiments*." Journal of Hazardous Materials, 179(1-3), pp 84-94; (2010).

[22] OR Hansen, J Renoult, SR Tieszen, & M Sherman. "*Validation of FLACS–HYDROGEN CFD consequence model against large-scale H2H2 explosion experiments in the FLAME Facility*." ICHS, Pisa 8–10 September, (2005).

[23] P Bénard et al. "*High Pressure Jets in the Presence of a Surface*", 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, Sept 11-13 (2007).