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HYRAM: A METHODOLOGY AND TOOLKIT FOR QUANTITATIVE RISK ASSESSMENT OF HYDROGEN SYSTEMS

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ABSTRACT

HyRAM is a methodology and accompanying software toolkit, which is being developed to provide a platform for integration of state-of-the-art, validated science and engineering models and data relevant to hydrogen safety. As such, the HyRAM software toolkit establishes a standard methodology for conducting quantitative risk assessment (QRA) and consequence analysis relevant to assessing the safety of hydrogen fueling and storage infrastructure. The HyRAM toolkit integrates fast-running deterministic and probabilistic models for quantifying risk of accident scenarios, for predicting physical effects, and for characterizing the impact of hydrogen hazards (thermal effects from jet fires, thermal and pressure effects from deflagrations and detonations). HyRAM incorporates generic probabilities for equipment failures for nine types of hydrogen system components, generic probabilities for hydrogen ignition, and probabilistic models for the impact of heat flux and pressure on humans and structures. These are combined with fast-running, computationally and experimentally validated models of hydrogen release and flame behavior. HyRAM can be extended in scope via user-contributed models and data. The QRA approach in HyRAM can be used for multiple types of analyses, including codes and standards development, code compliance, safety basis development, and facility safety planning. This manuscript discusses the current status and vision for HyRAM.

1.0 INTRODUCTION

This manuscript introduces HyRAM, a comprehensive methodology and accompanying software toolkit for assessing the safety of hydrogen fueling and storage infrastructure via Quantitative Risk Assessment (QRA) with integrated consequence analysis and/or stand-alone use of deterministic consequence models. The HyRAM software toolkit provides a consistent, documented methodology for QRA with integrated reduced-order physical models that have been validated for use in hydrogen systems. HyRAM also contains probabilistic data and models that have been vetted by the hydrogen research community. HyRAM is intended to facilitate evidence-based decision-making to support codes and standards development and compliance.

QRA has been an invaluable tool for the development and revision of hydrogen regulations, codes and standards (RCS). Significant reduction of separation distances were achieved in recent revisions of the NFPA 2 and 55 codes by quantify the risks of gaseous hydrogen releases [1]. In particular, QRA provides a framework for using science and engineering models and data to develop and revise codes and standards, as well as to facilitate the design and permitting process for hydrogen fueling stations and infrastructure. QRA can be used in RCS development (e.g., to establish requirements), or can be used to show compliance with those requirements (e.g., through a performance-based analysis). NFPA and SFPE provide guidance documents that establish a process for using QRA in development and revision of codes and standards [2, 3]. Since different tools and techniques may be appropriate in different contexts, neither organization provides a specific risk assessment method, tool, models or data.

Developers of two major hydrogen safety codes, NFPA 2 and ISO TC197, have been actively incorporating QRA and consequence modeling into the code development activities. Different approaches and models were used to develop separation distance requirements in NFPA 2 Chapter 7 [4], indoor fueling insight for NFPA 2 Chapter 10 [5], and safety distances for a draft of ISO 20100

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[6]. Each activity defined a similar approach, but differed in the use of models, assumptions, and data. The differences in the bases for the analyses stem from a combination of analysis choices and differences in availability of models and data.

The QRA process can generate important insights, but these insights are only as good as the information, methodology, data, and models used to conduct the analysis. A quality QRA incorporates a large amount of information spanning multiple disciplines. As noted in [7], QRA in hydrogen codes and standards applications currently suffers from inefficiency, requiring multiple experts to identify, integrate, and run the appropriate probabilistic and physical models. These modeling challenges form a barrier to the use of QRA by the code development committees. The deficiencies also affect the hydrogen industry personnel working to design systems compliant with the codes, suggest revisions to the code and apply for variances to codes necessitated by site-specific constraints.

Several research groups have identified gaps in data, models, and tools available for applying QRA on hydrogen system [5, 7-10]. At the same time, significant and ongoing international efforts on hydrogen safety, initiated under the auspices of the US DOE, the IEA HIA Tasks 19, 31 & 37, and HySafe, produce various first order engineering models, statistical models, empirical correlations and criteria for the myriad physical processes relevant to understanding the hazards associated with hydrogen systems [8, 9]. In 2014, the newly established IEA HIA Task 37 has also focused on developing an integration platform for hydrogen safety research. The goal of HyRAM is to integrate this hydrogen safety research 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.

The development of HyRAM was initiated to provide a consistent, flexible foundation for conducting hydrogen QRA with integrated consequence models, and to provide a foundation that could be expanded to accommodate new knowledge, models, and data. In essence, the HyRAM toolkit is intended to provide practical, efficient access to state-of-the-art models and data required to perform risk assessments of hydrogen systems.

2.0 MOTIVATION FOR HYRAM INTEGRATION PLATFORM

Since a quality QRA incorporates a large amount of information spanning multiple disciplines, comparison of QRAs is an especially challenging task. Many different research groups have conducted QRA activities on various aspects of hydrogen systems. In some cases, different groups conducting similar QRA activities experienced difficulty in comparing the analyses, which presented significant, direct challenges to international harmonization of hydrogen RCS [6]. Key differences among QRA activities were found in: analysis scope (e.g., which hazards were included, selection of metrics and criteria, defining system boundaries, defining failure events), the selected models and data (e.g., for system failures, ignition events, H2 release behavior, flame behavior, harm or damage), the resources used (e.g., modeling tools, information sources), and the documentation of the analysis.

These challenges motivate the need for a comprehensive, flexible modeling tool: one that integrates a wide range of scientific models and data into a single framework, and which gives analysts the flexibility to make different engineering choices (e.g., analysis goals, harm models) while still using the same, well-documented scientific basis and methodology. The underlying models, data, and assumptions should be *validated* (physical models should be experimentally validated in the range of use of the models; data should be as system-specific as possible) or if validation is not possible (e.g., human harm models, design-stage systems, risk acceptance criteria), the analysis should *transparent and documented.*

HyRAM is a model integration platform for comprehensive QRA, providing a unified language and architecture for models and data relevant to hydrogen safety. The development of a unified software framework also facilitates completeness and usability: experts from across the hydrogen safety research community can contribute validated models from their domain of expertise, and the hydrogen industry benefits from a “one-stop-shop” for those models.

3.0 TOOLKIT REQUIREMENTS

Requirements for an integrated toolkit were developed through international activities, coordinated within IEA HIA Task 31. One objective of IEA HIA Task 31 was to promote the development of a library of modern hazard assessment tools that contains best-available models and data relevant to understanding and quantifying risk in hydrogen technologies.

The derived requirements are as follows [11, 12]. 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
- Facilitate 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.
- 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 these defined requirements, multiple implementations can be envisaged. Additional requirements for the methods and models used within a toolkit are being established in ISO TC197 WG24. In the current approach, HyRAM is targeted toward US DOE domestic stakeholders (such as the NFPA 2 code committee and state fire marshals). In parallel, HySafe is coordinating the international community to “crowd-source” efforts to develop and host an open-source toolkit.

4.0 HYRAM METHODOLOGYAND MODELS

The HyRAM QRA methodology follows the general QRA approach shown in Figure 1. Square boxes denote HyRAM modules. HyRAM will contain at least one module for each element in Figure 1, with the flexibility for additional modules[1] contributed by the international hydrogen safety community. Concave boxes in Figure 1 denote analyst decisions, assumptions, and documentation activities which must be made and documented before HyRAM can be used. HyRAM is designed to be used as part of an iterative process of engaging with decision makers, as shown in the diamond box. The interfaces in HyRAM are designed to facilitate user activities such as comparison among various options (e.g., mitigations, system safety features) to support defining RCS requirements and to support demonstration of performance-based compliance with those requirements. Currently, the HyRAM toolkit is designed to model the two main hazards associated with releases of hydrogen: exposure to thermal radiation from flames, and exposure to overpressures from deflagrations/detonations.

[1] HyRAM is under active development. While the methodology in Figure 1 is not expected to change substantially, the models and data for each element will change. Current modules are relevant for gaseous hydrogen only. Several modules and interfaces are being developed at Sandia and among international researchers; coordination of the work is occurring through IEA HIA Task 37. The remainder of this section discusses prototype HyRAM version 1.0.0.390 from April 2015

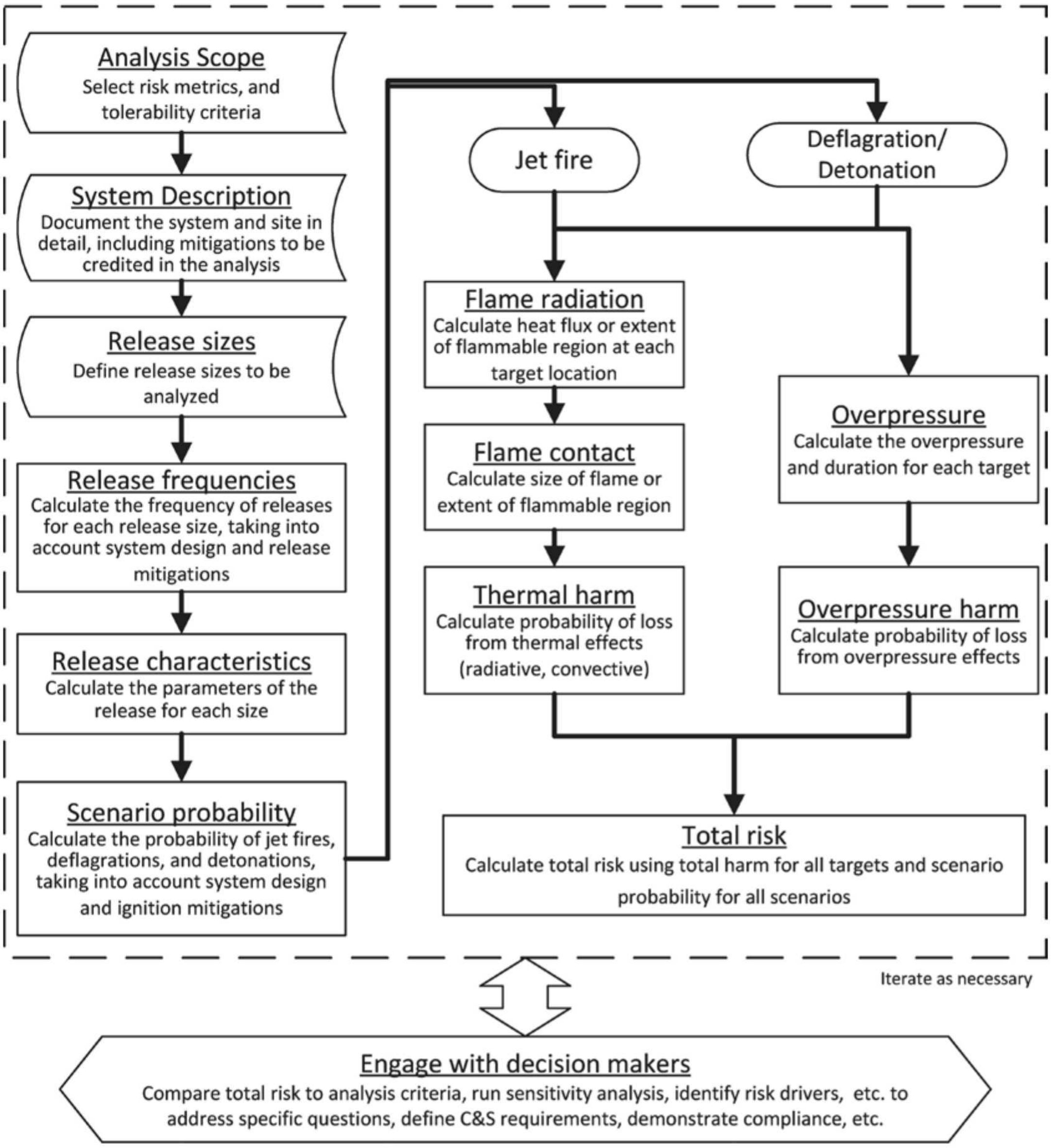

Figure 1: Summary of QRA methodology implemented in HyRAM toolkit

The HyRAM toolkit contains two user-interfaces – one that allows stand-alone implementation of the physical effects models for flames and overpressures and one for a QRA with those models. In general the approach outlined in Figure 1 uses a combination of probabilistic and deterministic models to evaluate the risk for a given system. The methodology uses traditional QRA probabilistic model approaches to assess the likelihood of various hydrogen release and ignition scenarios, which can lead to thermal and overpressure hazards. Several deterministic models are used together to characterize the physical effects for the scenarios. Information from the physical effect models is passed into probit functions that calculate consequences in terms of number of fatalities.

4.1. Analysis scopes supported by HyRAM

Determination of the scope of the analysis and selection of risk and/or harm criteria should be done before using HyRAM. HyRAM can be used to support analyses that involve use of risk and/or harm metrics. HyRAM results can be compared to defined acceptability or tolerability criteria (with due consideration of uncertainties) or against other HyRAM calculations (e.g., baseline system designs, prescriptive-compliant designs, etc.) [13].

HyRAM 1.0alpha supports calculation of the following risk metrics:

- Fatality risk metrics (Expected value)
  - FAR (Fatal Accident Rate) – number of fatalities per 100 million exposed hours
  - AIR (Average Individual Risk) – number of fatalities per exposed individual
  - PLL (Potential Loss of Life) – number of fatalities per system-year.
- Accident scenario metrics (Expected value):
  - Number of hydrogen releases per system-year (unignited and ignited cases)
  - Number of jet fires per system-year (immediate ignition cases)
  - Number of deflagrations/explosions per system-year (delayed ignition cases)

HyRAM 1.0alpha stand-alone physics models can be used to calculate the following thermal and overpressure consequences, which may be compared to harm criteria: jet flame temperature and trajectory as a function of position; radiative heat flux (kW/m^2) for a jet flame as a function of position. Currently HyRAM QRA mode accepts inputs from CFD to enable calculation of overpressure harm. The next version of HyRAM will also contain ability to calculate overpressure (*Pa*) generated from a deflagration event (caused by an indoor accumulation followed by a delayed ignition), as well as the concentration field of an unignited plume. Future HyRAM versions will also provide additional outputs from the physics models. For QRA outputs, future modifications will provide cut-sets for Fault Trees and reliability importance measures for risk scenarios. Additional modifications are planned to enable the output of probability distributions for many of the risk metrics above. On the physical model side, future modifications will provide ability to calculate physical effects of liquid hydrogen releases and subsequent ignitions. The models will also be updated to include the effects of a cross wind on plume and flame trajectories, and the submodels (e.g. the notional nozzle model, which describes the expansion of an underexpanded jet) will be kept current as scientific consensus changes.

4.2. System Description (HyRAM user input)

A QRA using HyRAM begins with a system description, which scopes out the system design and the operational environment. HyRAM is currently configured to conduct an analysis for a single system. The system description is specified by the system components (e.g. number of valves, length of pipe), system parameters (e.g. pipe dimensions, ambient conditions), and site/facility parameters (e.g. size of enclosure, number of occupants). Analysts would also retain additional documentation of the facility, including P&IDs, facility diagram, etc. In HyRAM, systems are broken down into nine types of components: Compressors, Cylinders, Valves, Instruments, Joints, Hose, Pipes (m), Filters, and Flanges. Users enter the number of components of each type. Users also input the following system operating parameters: Pipe outer diameter & wall thickness, internal temperature and pressure, External temperature and pressure, and annual number of demands (if a fault tree model is used). HyRAM supports both SI and Imperial units and includes native unit conversion features. User input for the site/facility includes facility dimensions[2] (length, width, height), population (number of occupants or potential exposed persons, number of exposed hours (for each person). Users also enter the parameters of probability distributions which randomly assign positions for each person: current options are normal distribution ((minimum distance from system, standard deviation based on site size) or uniform distribution (minimum distance from system, maximum distance from system).

Future versions of HyRAM will allow input of multiple systems. The spatial specifications will also be more rigorous in a future version. For example, the location of each component will be specified, and the location of the exposed persons will need to be tracked.

4.3. Release sizes

For each component, the probability of a leak of a given size must be specified. In HyRAM, the release is discretized into five size categories: 0.01%, 0.1%, 1%, 10%, 100% of dispenser pipe flow area. Future versions of HyRAM will support additional levels of discretization, and longer term

[2] Currently a placeholder to be used for planned features.

revisions will include dynamic features, e.g., ability to generate possible release sizes through sampling over a defined distribution for size of release from each component.

4.4. Release frequencies and scenarios

Table 1: Default ignition probabilities in HyRAM [14]

Hydrogen release rate (kg/s)	Immediate Ignition Probability	Delayed Ignition Probability
<0.125	0.008	0.004
0.125 - 6.25	0.053	0.027
>6.25	0.23	0.12

The event sequence diagram (ESD) in Figure 2 illustrates the possible scenarios that could occur after a hydrogen release. There are four possible outcomes from a hydrogen release scenario: unignited release, jet fire, accumulated gas fire (H2/air mixtures) without overpressure (OP) effects and accumulated gas fire with overpressure effects. The colors denote which harm models (described in Sec. 4.6) are associated with each end state: end states in green are not associated with any harm model; end states in yellow are associated with thermal harm models; end states in red are associated with overpressure harm models. The ESD includes several pivotal events, which influence the occurrence of the end states. The first event is leak isolation. If the leak is isolated[3] before ignition occurs, the result is an unignited release. If the leak is not isolated, there is potential for immediate ignition or delayed ignition. Immediate ignition of a hydrogen release is assumed to result in a jet fire, and delayed ignition of a hydrogen release is assumed to result in combustion of a premixed flame (deflagration or detonation event), which is termed an accumulated gas fire in the model in Figure 2; the results of this may be dominated by thermal effects or pressure effects. If ignition does not occur, the model terminates with the unignited release.

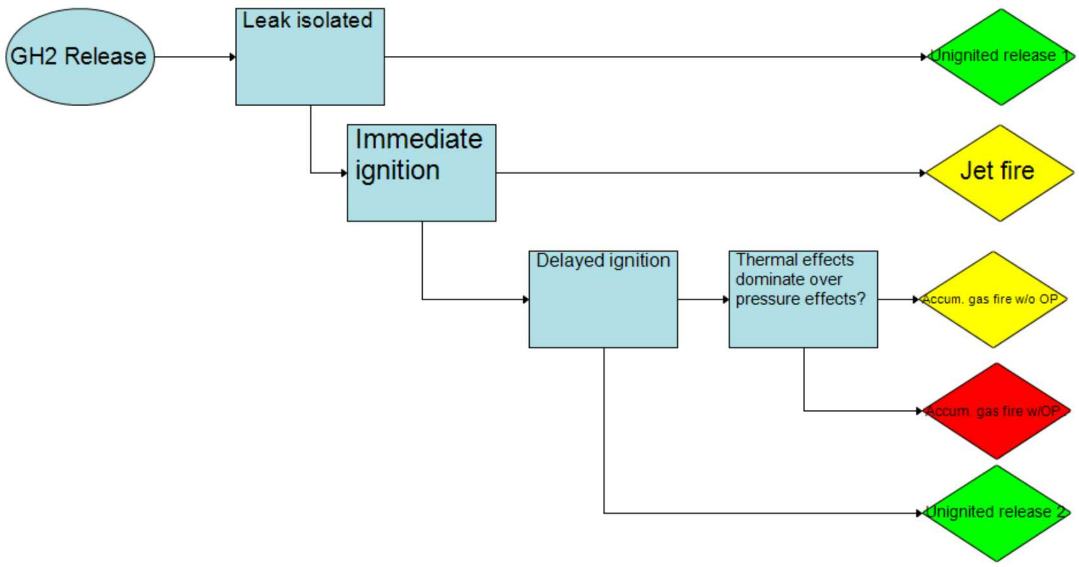

Figure 2: Event Sequence Diagram documented the possible scenarios that could occur after a hydrogen release.

Currently, the scenarios and associated probability expressions can only be changed in the source code for HyRAM. A future version of HyRAM will allow graphical editing of ESDs. The initiating event in the model is a release of gaseous hydrogen (GH_2 Release).

[3] This event can be toggled on and off in the current model. If the event is toggled off, the probability of leak isolation is set to 0.0. If the event is toggled on, the event probability is set to the default probability defined in the HyRAM source code. This default probability for successful leak isolation is 0.1/demand; it can also be changed in HyRAM source code.

The frequency of the initiating event (GH2 Release) comes from implementation of a parts-count approach, as described in SAND2009-0874 [4]. HyRAM also contains default data for component leak frequency published in [4]; this data is presented in Appendix A. Users can modify this data directly in the HyRAM graphical user interface. HyRAM also contains hooks for combining information on non-leak contributors to the initiating event through a Fault Tree (FT) approach. Currently both the cut-sets and the associated basic event probabilities must be manually identified and written into HyRAM source code. In a future version of HyRAM, users will be able to graphically modify FTs and generate cut-sets within HyRAM using the capabilities of the hybrid causal logic algorithm [15].

The default hydrogen ignition probabilities in HyRAM were developed by the Canadian Hydrogen Safety Program [14]; these are shown in Table 1. This approach provides immediate and delayed ignition probability as a function of hydrogen release rate. HyRAM also allows user-defined ignition probability tables of a similar format. The hydrogen release rate is calculated using the physical models described in Section 4.5.

4.5. Consequence models: Hydrogen Behavior Models

4.5.1. Gas release, dispersion and accumulation

HyRAM currently contains validated physics models for several behaviors associated with gaseous hydrogen. Hydrogen system pressures are generally above the critical pressure ($\approx 1.9 \times P_{atm}$), so the gas flows at the speed of sound but remains at a pressure above atmospheric on the ambient side of the leak. As this so-called under-expanded jet expands to atmospheric pressure, a complex shock structure forms. Downstream of the shock structure, canonical hyperbolic decay rates of the centerline velocity, concentration, etc. for subsonic jets are observed in these under-expanded jets. However, the equivalent subsonic source for the observed fields is necessary to use the canonical correlations for the jet behavior. A notional nozzle is used to calculate an effective release diameter, velocity, and thermodynamic state after the complex shock structure. Ruggles and Ekoto [16] provide a more comprehensive description of the notional nozzle models implemented in HyRAM.

The effective release characteristics are used as inputs to a one-dimensional model that conserves mass and momentum along the streamline of the jet. This one-dimensional model assumes that the radial profiles for velocity, concentration, etc. have a Gaussian shape, and accounts for air entrainment and buoyancy. More details about this simplified model can be found in [17]. If this plume occurs in an enclosure, the fill-box model of Lowesmith et al. [18] is used to calculate the volumetric accumulation and concentration of gas in the enclosure.

The flexible architecture of the HyRAM framework enables the incorporation of additional physical models, including liquid hydrogen release and dispersion. A one-dimensional model for a liquid hydrogen jet, that includes energy conservation along with the mass and momentum conservation previously described, has been developed [19]. A lack of validation data for this model has prompted the development of an experiment at Sandia [20].

4.5.2. Combustion properties

The trajectory and properties of a jet flame are calculated using the model described by Ekoto et al. [21], which includes buoyancy and wind corrections. This one-dimensional model is similar to the jet model described above, except rather than conserving the mass of hydrogen, the mixture fraction is conserved along the jet trajectory. Once the properties of the flame are calculated, the radiative heat-flux is calculated one of two ways. Either the centroid of the flame is used a single-point source of the radiative energy, or the flame is discretized along its trajectory and the heat flux contributions are summed, in a weighted multi-source radiation model [22].

Although not yet implemented in HyRAM 1.0alpha, the current beta version of HyRAM includes a model for the overpressure resulting from the ignition of a flammable mass in an enclosure. The accumulation model described in the previous section is used to calculate the flammable mass. The volume expansion on combustion is used to calculate the peak overpressure in the enclosure.

4.6. Harm models for thermal and overpressure exposures

HyRAM contains several probit models that can be used to predict harm from thermal exposures and from blast overpressures. Probit models are used to establish the probability of injury or fatality for a given exposure. Several probit models were reviewed in [23] and are included in HyRAM.

For thermal radiation, the harm level is a function of both the heat flux intensity and the duration of exposure. Harm from radiant heat fluxes is often expressed in terms of a thermal dose unit (V) which combines the heat flux intensity and exposure time: $V = I^{(4/3)\times t}$ where I is the radiant heat flux in W/m^2 and t is the exposure duration in seconds. HyRAM allows user to decide between thermal probits from [24-27]; additional models could be added through HyRAM source code changes.

For overpressure exposures, probit models account for direct effects of pressure (e.g., pressure-induced damage to pressure-sensitive organs such as the lungs and ears) and indirect effects. (e.g., collapse of structures, impact from fragments and debris). Large explosions can also carry a person some distance resulting in injury from collisions with structures or from the resulting violent movement. The probit models for the effects of overpressures that are included in HyRAM are from [26, 28, 29]; additional models could be added through HyRAM source code changes.

CONCLUSION

HyRAM provides a platform which integrates state-of-the-art, validated science and engineering models and data relevant to hydrogen safety into a comprehensive, industry-focused decision support system. The use of a standard platform for conducting hydrogen QRA ensures that various industry stakeholders can produce metrics for safety from defensible, traceable calculations. The physical models underlying the HyRAM platform have been experimentally validated with hydrogen in the parameter (e.g., pressure, temperature) range of interest for hydrogen systems. The probability data included in HyRAM have been developed by reference to systems using hydrogen as much as possible. The software architecture of HyRAM is modular, with the anticipated addition and revision of modules and data as the state-of-the-art advances.

In this manuscript, we have presented the scientific models, data, and QRA methodology included in the prototype HyRAM 1.0alpha software that has been released to a limited set of users. The current release allows users to define a single system with a hard-coded event sequence scenario. This software release includes calculations for thermal hazards, and a working version includes calculations for an overpressure hazard. Several probit models are also included to calculate the harm from these hazards. We also presented our vision for the HyRAM platform. Two important areas of development are validation of the physics models for cryogenic hydrogen systems, and rigorous tracking of components and people spatially.The HyRAM toolkit and methodology provides a practical, efficient method for conducting QRA, and access to state-of-the-art, validated models and data to use in QRA and consequence analysis. While HyRAM has already had impact on hydrogen safety, realization of the full potential of HyRAM requires continued investment from the research community.

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REFERENCES

[1] Harris AP, Dedrick DE, LaFleur C, San Marchi C. Safety, Codes and Standards for Hydrogen Installations: Metrics Development and Benchmarking. Albuquerque, NM: Sandia National Laboratories; 2014. SAND2014-3416.

[2] Rose SE, Flamberg S, Leverenz F. Guidance Document for Incorporating Risk Concepts into NFPA Codes and Standards. Fire Protection Research Foundation; 2007.

[3] Society of Fire Protection Engineers. SFPE Engineering Guide to Performance-Based Fire Protection: analysis and design of buildings. Quincy, MA, USA: National Fire Protection Association; 2007.

[4] LaChance J, Houf W, Middleton B, Fluer L. Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards. Albuquerque, NM: Sandia National Laboratories; 2009. SAND2009-0874.

[5] Groth KM, LaChance JL, Harris AP. Early-Stage Quantitative Risk Assessment to Support Development of Codes and Standard Requirements for Indoor Fueling of Hydrogen Vehicles. Albuquerque, NM: Sandia National Laboratories; 2012. SAND2012-10150.

[6] LaChance JL, Middleton B, Groth KM. Comparison of NFPA and ISO approaches for evaluating separation distances. International Journal of Hydrogen Energy. 2012 November;37(22):17488–17496.

[7] Groth K, Harris A. Hydrogen Quantitative Risk Assessment Workshop Proceedings. Albuquerque, NM: Sandia National Laboratories; 2013. SAND2013-7888.

[8] Kotchourko A, Baraldi D, Benard P, Eisenreich N, Jordan T, Keller J, et al. State of the art and research priorities in hydrogen safety. Joint Research Centre of the European Commission (JRC); 2014.

[9] LaChance J, Tchouvelev A, Ohi J. Risk-informed process and tools for permitting hydrogen fueling stations. International Journal of Hydrogen Energy. 2009;34(14):5855–5861.

[10] Pasman HJ. Challenges to improve confidence level of risk assessment of hydrogen technologies. International Journal of Hydrogen Energy. 2011;36(3):2407–2413.

[11] Groth KM, Tchouvelev AV. A toolkit for integrated deterministic and probabilistic risk assessment for hydrogen infrastructure. In: Proceedings of the International Conference on Probabilistic Safety Assessment and Management (PSAM 12). Honolulu, HI; 2014. .

[12] Tchouvelev AV, Groth KM, Benard P, Jordan T. A Hazard Assessment Toolkit For Hydrogen Applications. In: Proceedings of the 20th World Hydrogen Energy Conference (WHEC 2014); 2014. .

[13] LaFleur AC, Muna AB, Groth KM. Fire Protection Engineering Design Brief Template: Hydrogen Refueling Station. Albuquerque, NM: Sandia National Laboratories; 2015. SAND2015-4500.

[14] Canadian Hydrogen Safety Program. Quantitative Risk Comparison of Hydrogen and CNG Refueling Options. Presentation at IEA Task 19 Meeting; 2006.

[15] Groth K, Wang C, Mosleh A. Hybrid causal methodology and software platform for probabilistic risk assessment and safety monitoring of socio-technical systems. Reliability Engineering and System Safety. 2010;95(12):1276–1285.

[16] Ruggles AJ, Ekoto IW. Ignitability and mixing of underexpanded hydrogen jets. International Journal of Hydrogen Energy. 2012 November;37(22):17549–17560.

[17] Houf W, Schefer R. Analytical and experimental investigation of small-scale unintended releases of hydrogen. International Journal of Hydrogen Energy. 2008;33(4):1435–1444.

[18] Lowesmith BJ, Hankinson G, Spataru C, Stobbart M. Gas build-up in a domestic property following releases of methane/hydrogen mixtures. International Journal of Hydrogen Energy. 2009;34(14):5932–5939.

[19] Houf WG, Winters WS. Simulation of high-pressure liquid hydrogen releases. International Journal of Hydrogen Energy. 2013;38(19):8092–8099.

[20] Ekoto IW, Hecht E, San Marchi C, Groth KM, LaFleur AC, Natesan N, et al. Liquid Hydrogen Release and Behavior Modeling: State-of-the-Art Knowledge Gaps and Research Needs for Refueling Infrastructure Safety. Albuquerque, NM: Sandia National Laboratories; 2014. SAND2014-18776.

[21] Ekoto IW, Ruggles AJ, Creitz LW, Li JX. Updated jet flame radiation modeling with buoyancy corrections. International Journal of Hydrogen Energy. 2014;39(35):20570–20577.

[22] Hankinson G, Lowesmith BJ. A consideration of methods of determining the radiative characteristics of jet fires. Combustion and Flame. 2012;159(3):1165–1177.

[23] LaChance J, Tchouvelev A, Engebø A. Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure. International Journal of Hydrogen Energy. 2011;36(3):2381–2388.

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

[25] Lees FP. The assessment of major hazards: a model for fatal injury from burns. Process safety and environmental protection. 1994;72(3):127–134.

[26] TNO. Methods for the determination of possible damage. The Netherlands Organization of Applied Scientific Research (TNO); 1992. CPR 16E.

[27] Tsao CK, Perry WW. Modifications to the vulnerability model: a simulation system for assessing damage resulting from marine spills. U. S. Coast Guard; 1979. ADA 075 231.

[28] Center for Chemical Process Safety (CCPS). Guidelines for Chemical Process Quantitative Risk Analysis. American Institute of Chemical Engineers; 1999.

[29] Health and Safety Executive (HSE). Major hazard aspects of the transport of dangerous substances; 1991.

APPENDIX A: GH2 RELEASE DATA

Table 2 contains HyRAM default data for leak frequencies for hydrogen components. The probabilities were developed from a Bayesian updating process using generic leak probabilities and available hydrogen data. The development of these probabilities is documented in SAND2009-0874.

Mu and sigma are parameters of the lognormal distribution. These parameters can be used to estimate average (mean) leak rates or to propagate uncertainty about leak rates. These parameters are used to calculate the probability of random leaks from a system.

Table 2: HyRAM default data (parameters of lognormal distribution) for leak frequencies of hydrogen components.

Component	Leak size	μ	σ	Mean (Calculated)	Variance (Calculated)
Compressors	0.01%	−1.72	0.21	1.83×10^{-1}	1.58×10^{-3}
	0.1%	−3.92	0.48	2.23×10^{-2}	1.32×10^{-4}
	1%	−5.14	0.79	8.01×10^{-3}	5.55×10^{-5}
	10%	−8.84	0.84	2.06×10^{-4}	4.31×10^{-8}
	100%	−11.34	1.37	3.04×10^{-5}	5.11×10^{-9}
Cylinders	0.01%	−13.84	0.62	1.18×10^{-6}	6.46×10^{-13}
	0.1%	−14.00	0.61	9.98×10^{-7}	4.43×10^{-13}
	1%	−14.40	0.62	6.80×10^{-7}	2.19×10^{-13}
	10%	−14.96	0.63	3.90×10^{-7}	7.36×10^{-14}
	100%	−15.60	0.67	2.09×10^{-7}	2.47×10^{-14}
Filters	0.01%	−5.25	1.98	3.77×10^{-2}	7.18×10^{-2}
	0.1%	−5.29	1.52	1.60×10^{-2}	2.30×10^{-3}
	1%	−5.34	1.48	1.44×10^{-2}	1.64×10^{-3}
	10%	−5.38	0.89	6.87×10^{-3}	5.67×10^{-5}
	100%	−5.43	0.95	6.94×10^{-3}	7.16×10^{-5}
Flanges	0.01%	−3.92	1.66	7.86×10^{-2}	9.13×10^{-2}
	0.1%	−6.12	1.25	4.82×10^{-3}	8.84×10^{-5}
	1%	−8.33	2.20	2.72×10^{-3}	9.41×10^{-4}
	10%	−10.54	0.83	3.74×10^{-5}	1.41×10^{-9}
	100%	−12.75	1.83	1.55×10^{-5}	6.53×10^{-9}
Hoses	0.01%	−6.81	0.27	1.15×10^{-3}	9.82×10^{-8}
	0.1%	−8.64	0.55	2.06×10^{-4}	1.51×10^{-8}
	1%	−8.77	0.54	1.79×10^{-4}	1.11×10^{-8}
	10%	−8.89	0.55	1.60×10^{-4}	8.92×10^{-9}
	100%	−9.86	0.85	7.47×10^{-5}	5.82×10^{-9}
Joints	0.01%	−9.57	0.16	7.05×10^{-5}	1.35×10^{-10}
	0.1%	−12.83	0.76	3.56×10^{-6}	9.84×10^{-12}
	1%	−11.87	0.48	7.80×10^{-6}	1.54×10^{-11}
	10%	−12.02	0.53	6.96×10^{-6}	1.57×10^{-11}
	100%	−12.15	0.57	6.21×10^{-6}	1.45×10^{-11}
Pipes	0.01%	−11.86	0.66	8.78×10^{-6}	4.16×10^{-11}
	0.1%	−12.53	0.69	4.57×10^{-6}	1.26×10^{-11}
	1%	−13.87	1.13	1.80×10^{-6}	8.27×10^{-12}
	10%	−14.58	1.16	9.12×10^{-7}	2.33×10^{-12}
	100%	−15.73	1.71	6.43×10^{-7}	7.39×10^{-12}
Valves	0.01%	−5.18	0.17	5.71×10^{-3}	9.90×10^{-7}
	0.1%	−7.27	0.40	7.50×10^{-4}	9.67×10^{-8}
	1%	−9.68	0.96	9.92×10^{-5}	1.49×10^{-8}
	10%	−10.32	0.68	4.13×10^{-5}	9.86×10^{-10}
	100%	−12.00	1.33	1.49×10^{-5}	1.09×10^{-9}
Instruments	0.01%	−7.32	0.68	8.31×10^{-4}	4.00×10^{-7}
	0.1%	−8.50	0.79	2.78×10^{-4}	6.80×10^{-8}
	1%	−9.06	0.90	1.73×10^{-4}	3.68×10^{-8}
	10%	−9.17	1.07	1.84×10^{-4}	7.18×10^{-8}
	100%	−10.20	1.48	1.11×10^{-4}	9.85×10^{-8}