Hydrogen Quantitative Risk Assessment

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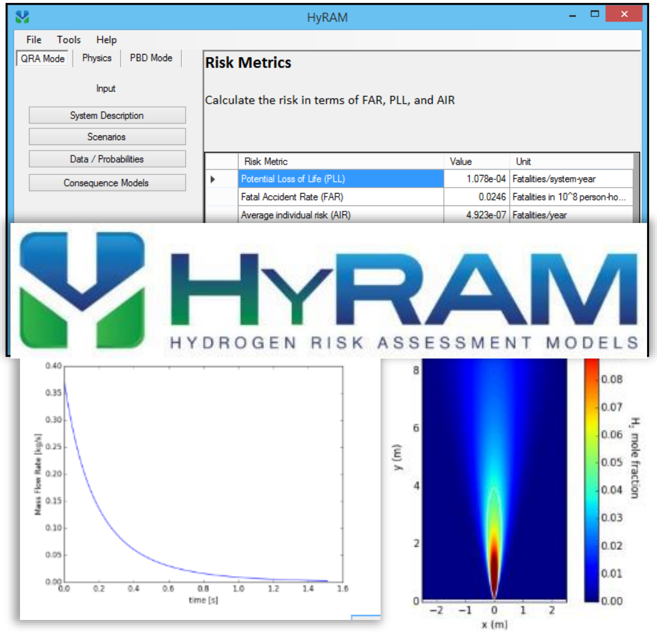
May 1, 2019



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Overview

Timeline

- Project start date: Oct. 2003
- Project end date: Sept. 2019*

  * Project continuation and direction determined by DOE annually.

Barriers

A. Safety Data and Information: Limited Access and Availability

F. Enabling National and International Markets Requires Consistent RCS

K. No Consistent Codification Plan and Process for Synchronization of R&D and Code Development

L. Usage and Access Restrictions – Parking Structures, Tunnels and Other Usage Areas

Budget

- FY18 DOE Funding: $325K
- Planned FY19 DOE Funding: $700K

Partners

Industry & research collaborators:
Linde, FirstElement Fuel, PNNL, NREL, Air Liquide, Quong & Associates, HySafe, 40+ organizations using HyRAM

SDO/CDO participation:
NFPA 2/55, DOT Tunnel Jurisdictions, H2USA, CaFCP, FPRF

International engagement:
IPHE

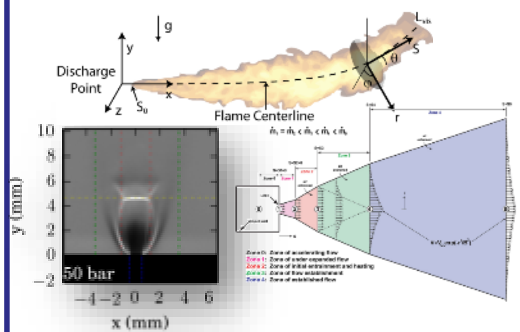
Relevance

Objective: Develop a rigorous **scientific & engineering basis** for assessing safety risk of H_2 systems and **facilitate the use of that information** for revising RCS for emerging hydrogen technologies.

Barrier from 2015 SCS MYRDD	SNL Goal
A. Safety Data and Information: Limited Access and Availability	Build validated H2 behavior physics models that enable industry-led C&S revision and Quantitative Risk Assessment (QRA).
F. Enabling National and International Markets Requires Consistent RCS	Develop H_2-specific QRA tools & methods which support SCS decisions.
K. No Consistent Codification Plan and Process for Synchronization of R&D and Code Development	Apply H2-specific QRA tools & methods to support code improvement and to enable risk-equivalent code compliance option.
L. Usage and Access Restrictions – Parking Structures, Tunnels and Other Usage Areas	Develop scenario specific analysis of hydrogen behavior and consequences and evaluate mitigation features.

Project Approach: *Coordinated activities* to enable consistent, rigorous, and accepted safety analysis

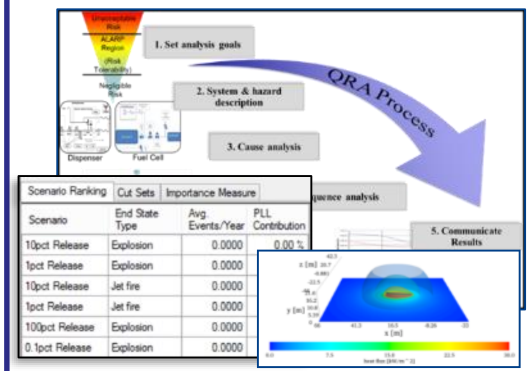
Behavior R&D



Develop and validate scientific models

to accurately predict hazards and harm from liquid releases, flames, etc.

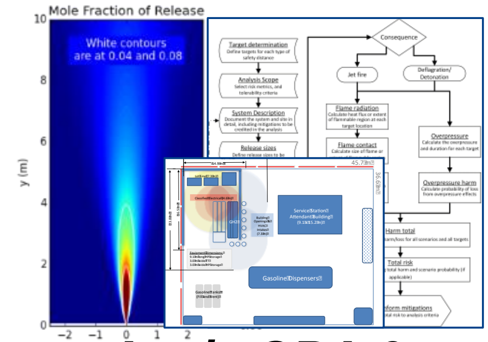
Risk R&D



Develop integrated methods and algorithms

for enabling consistent, traceable and rigorous QRA

Application in SCS



Apply QRA & behavior models to real problems

in hydrogen infrastructure and emerging technology

Developing methods, data, tools for H_2 safety & SCS

Approach / FY18-19 Milestones

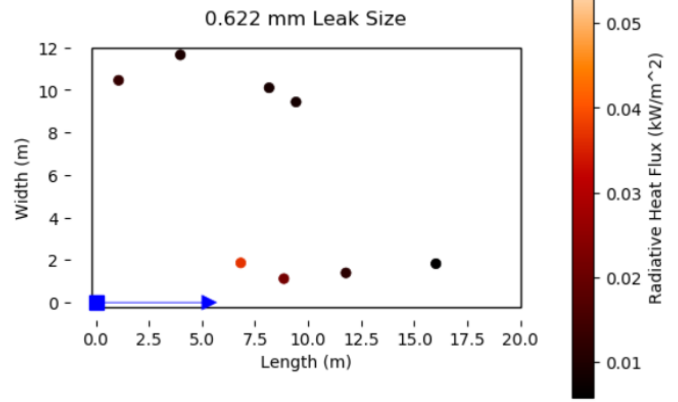
Impact Areas	Completion date or status
Liquid hydrogen QRA methodology development	
• Develop & integrate QRA flexibility into HyRAM • Pursue copyright & open-source license for HyRAM 2.0 • Develop LH2 leak frequencies • Develop risk-informed separation distance proposals to code	Feb. 2019 On track for June 2019 Ongoing 2020
Real world application of Alternative Means	
• Drafting paper on alternative means & measures	Ongoing
Evaluation of tunnels for FCEV safety	
• Research priorities workshop on H2 safety- tunnel focus • Drafting white paper based on tunnel workshop results • Research with federal highway and other stakeholders to address all US tunnels	Sept. 2018 On track for Sept. 2019 Ongoing
International harmonization of standards for hydrogen infrastructure	
• IPHE RCS Workshop on Tunnel Safety & Hydrogen • Hosted NFPA 2/55 bulk H2 storage task group	Sept. 2018 Oct. 2018

Accomplishment: Expanded HyRAM QRA flexibility beyond hydrogen refueling stations

- Developed additional QRA capability to enable HyRAM to be applied to a larger variety of H2 applications
  - Users able to edit the parameters of the existing fault tree (FT) or substitute their user-defined FT results from external FT software
  - Updated HyRAM methodology enables users to alter the risk analysis for different applications
- Latest release can be found at http://hyram.sandia.gov

Risk Metrics | Scenario Ranking | Cut Sets | Plots

	Rank	Scenario	End State Type	Avg. Events/Year	Branch Line Probability	PLL Contribution
▸	1	000.01% Release	Shutdown	0.0313728769	90.00000000%	0.00000000%
	2	000.01% Release	Jet fire	0.0000278870	0.08000000%	0.17909659%
	3	000.01% Release	Explosion	0.0000138320	0.03968000%	0.04406063%
	4	000.01% Release	No ignition	0.0034441563	9.88032000%	0.00000000%
	5	000.10% Release	Shutdown	0.0045062884	90.00000000%	0.00000000%
	6	000.10% Release	Jet fire	0.0000040056	0.08000000%	0.02572480%
	7	000.10% Release	Explosion	0.0000019868	0.03968000%	0.00632871%
	8	000.10% F				
	9	001.00% F				
	10	001.00% F				
	11	001.00% F				
	12	001.00% F				
	13	010.00% F				
	14	010.00% F				
	15	010.00% F				
	16	010.00% F				
	17	100.00% F				
	18	100.00% F				
	19	100.00% F				
	20	100.00% F				



Expanded QRA flexibility will allow for hydrogen safety analysis for new H2 technologies.

Progress: HyRAM licensing and AltRAM

- Pursuing a General Public License (GPL) open source license
  - Will allow researchers to view and download the source code
  - Additional changes can now be added back to HyRAM
- HyRAM 2.0 going through technical advance/copyright process
- HyRAM 2.0 will be merged into Alternative Fuels Risk Assessment Modules (AltRAM)
  - Incorporate risk and physics models for CNG, LNG and propane
  - Open source format will support AltRAM development

Providing HyRAM source code to larger research community will allow others to contribute to the development of HyRAM

Progress: Science-based liquid separation distances

- Goal: Develop leak frequencies and other data needed to support the NFPA 2/55 separation distance task group
- Progress:
  - In-person meeting held in October 2018 to determine next steps
  - Generated a leak frequency template and are working with industry partners to develop consistent set of data
  - LNG leak frequencies developed as a first step
  - LH2 release model being added to HyRAM

Specific Component Type	Severity	Frequency	Units	Leak Size Description
Piping				
Pipe Diameter (d) < 50 mm	Rupture	1.00E-06	Per Meter Year	100% cross sectional area
d < 50 mm	Major	5.00E-06	Per Meter Year	1" (25 mm)
50 mm ≤ d < 149 mm	Rupture	5.00E-07	Per Meter Year	100% cross sectional area
50 mm ≤ d < 149 mm	Medium	2.00E-06	Per Meter Year	1" (25 mm)
150 mm ≤ d < 299 mm	Rupture	2.00E-07	Per Meter Year	100% cross sectional area
150 mm ≤ d < 299 mm	Major	4.00E-07	Per Meter Year	1/3 of pipe diameter
150 mm ≤ d < 299 mm	Minor	7.00E-07	Per Meter Year	1" (25 mm)
300 mm ≤ d < 499 mm	Rupture	7.00E-08	Per Meter Year	100% cross sectional area
300 mm ≤ d < 499 mm	Major	2.00E-07	Per Meter Year	1/3 of pipe diameter
300 mm ≤ d < 499 mm	Medium	4.00E-07	Per Meter Year	2" (50 mm)
300 mm ≤ d < 499 mm	Minor	5.00E-07	Per Meter Year	1" (25 mm)
500 mm ≤ d < 1000 mm	Rupture	2.00E-08	Per Meter Year	100% cross sectional area
500 mm ≤ d < 1000 mm	Major	1.00E-07	Per Meter Year	1/3 of pipe diameter
500 mm ≤ d < 1000 mm	Minor	2.00E-07	Per Meter Year	2" (50 mm)
500 mm ≤ d < 1000 mm	Very Small	4.00E-07	Per Meter Year	1" (25 mm)

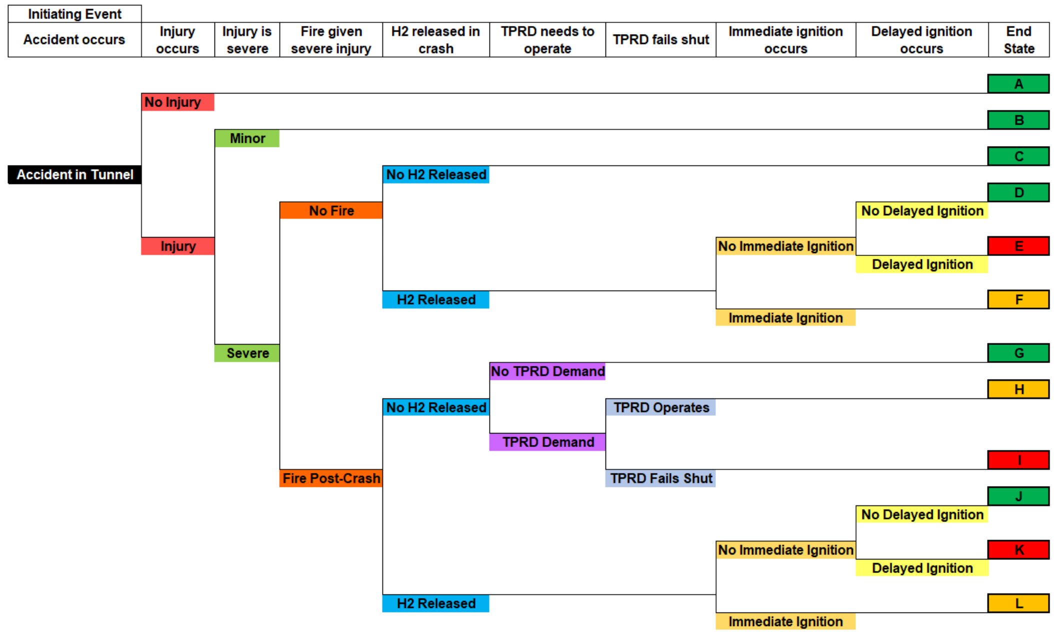
Risk-informed code requirements based on risk threshold revisions enable more sites to readily accept hydrogen infrastructure

Progress: Real World Application of Alternate Means

- Goal: Establish alternate means as a viable station permitting option with an industry partner
- Progress:
  - CRADA with industry partner (FirstElement Fuel, Inc.)
  - Drafting report documenting Alternate Means methodology
  - Report could be used for a station with separation distance challenges
  - Report will be published for larger community

Demonstrating alternate means of compliance:
- Increases options for industry in siting hydrogen fueling stations
- Overall confidence in the performance-based approach for station design

Progress: Tunnels safety study



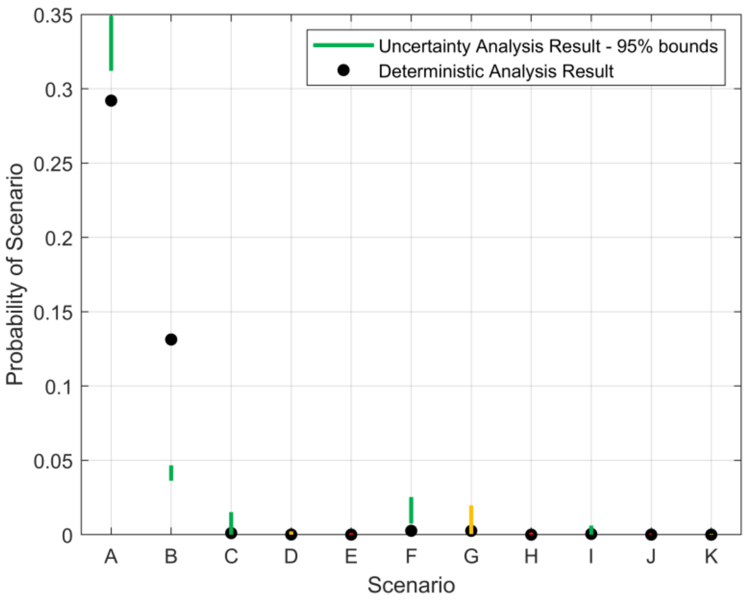
Ehrhart, Brian D., Brooks, Dusty M., Muna, Alice B., LaFleur, Chris, "Risk Assessment of Hydrogen Fuel Cell Vehicles in Tunnels," Accepted by Fire Technology Journal.

- Establishment of a joint collaboration between DOE/DOT
- IPHE RCSS initiated tunnel safety workshop with issues identified in a whitepaper
- Journal article on risk assessment of HFCV in tunnels accepted for publication
- Probabilities addressing uncertainty for different tunnel scenarios have been established

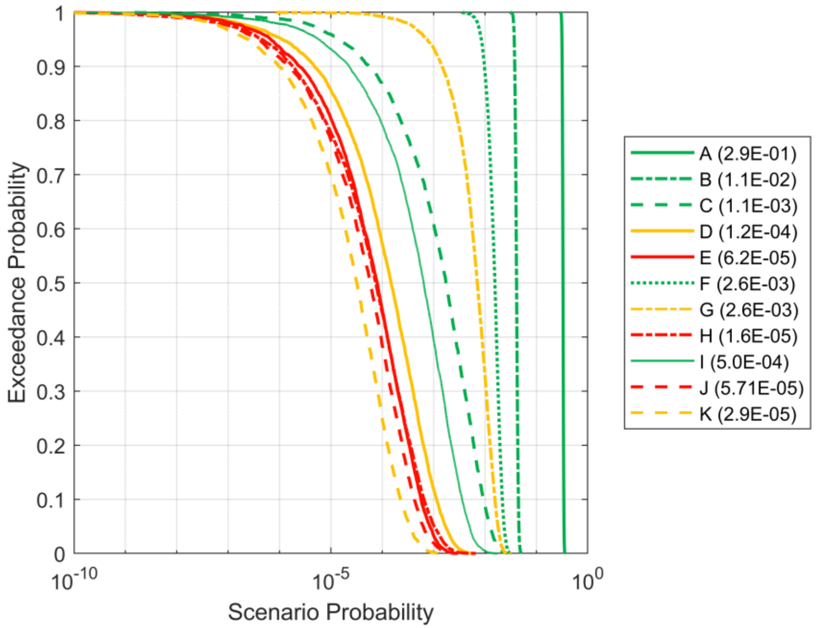
Addressing tunnels on a federal basis enables the deployment of fuel cell vehicles in other parts of the US

Accomplishment: Uncertainty around scenario probabilities

Uncertainty Quantification on Deterministic Scenario Probabilities



Complimentary Cumulative Distribution Functions: Exceedance Probability Curves



Calculation of uncertainty allows a more complete range of answers to be characterized

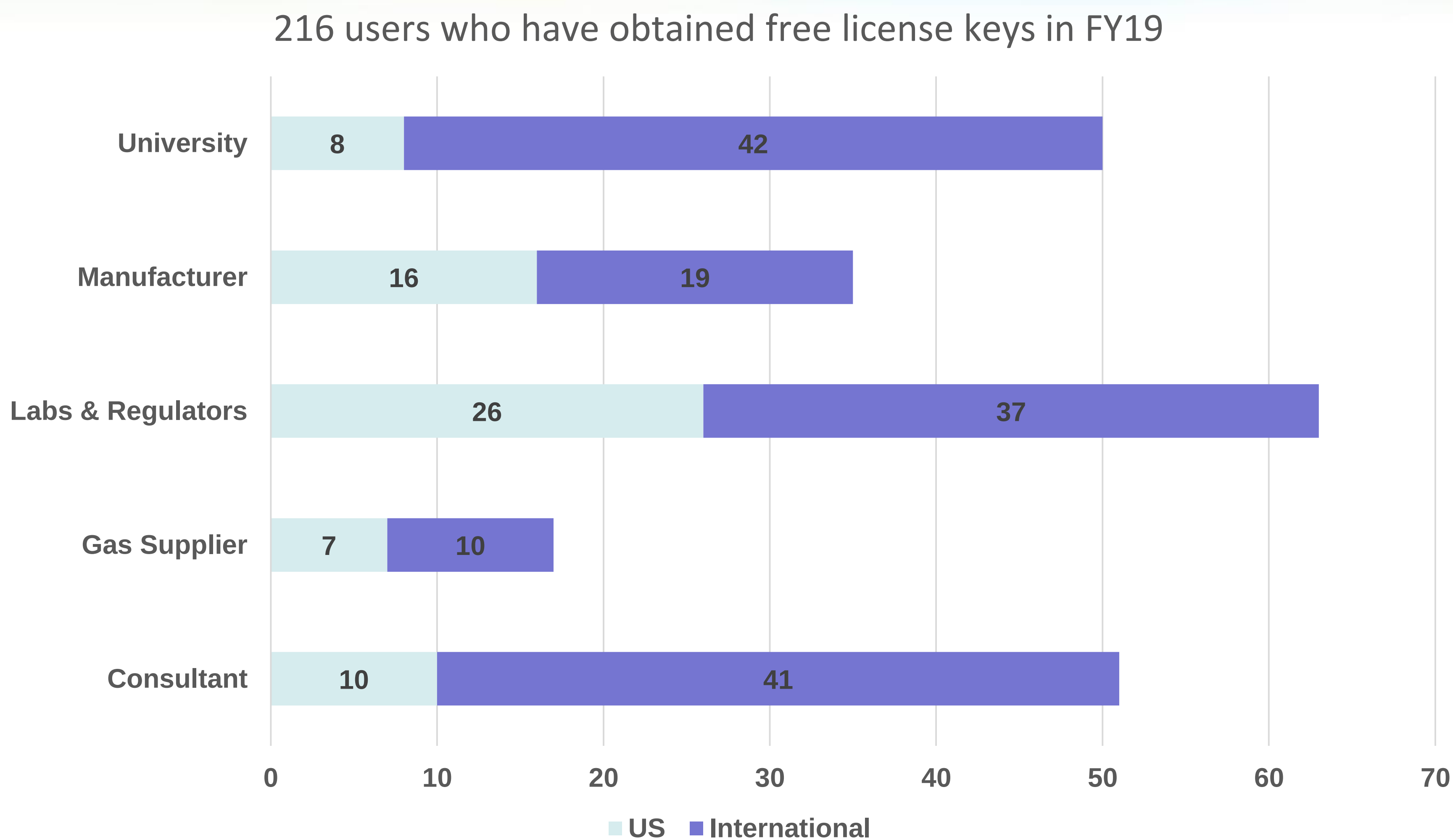
Responses to previous year reviewer's comments

- *AMR2018 comment: The project weakness is that the scope of the tools in the past has been focused on infrastructure.*
  - There are many areas where additional modules and data could enhance the RCS and adding flexibility to the QRA portion of HyRAM will allow for analyses to be conducted for more applications.
- *AMR2018 comment: It is suggested that the team consider or review the value of a performance-based design approach to alternate methods of code compliance using QRA versus other approaches or methods of demonstrating code compliance, such as alternate materials and methods justifications.*
  - We are working on developing reports to address this issue with new CRADA collaborators.
- *AMR2018 comment: It is also recommended that the team publish the tunnel risk modeling, along with a comparison of today's gasoline/diesel vehicles.*
  - We are working on a paper comparing gasoline/diesel vehicles and also other alternative fuel vehicles to hydrogen in tunnels.

Collaborations: Partners, RCS participation & international engagement

Relationship	Partner	Role
CRADA (Signed)	**Linde Group**, Industrial gas supplier	In-kind support, data exchange for QRA tool, PBD activities, LH2 laboratory
CRADA (Signed)	**FirstElement Fuel**, Station Developer	In-kind support, data exchange for QRA tool, PBD activities
CRADA (Signed)	**Frontier Energy,** (Manager of the California Fuel Cell Partnership)	Develop industry stakeholders in support of LH2 Behavior Characterization
CRADA (Signed)	**Fire Protection Research Foundation (NFPA)**	Lead stakeholder oversight panel and enable link to NFPA code process
CRADA (Signed)	**Air Liquide**, Industrial gas supplier	Research on LH2 releases and QRA
CRADA (Signed)	**Quong & Associates**, Industry consultants	Research on GH2 releases in maintenance facilities
Code Committee Members	**NFPA 2, 55**	Separation distances task group, enclosures task group, and permitting task group.
Collaborator	**Pacific Northwest National Laboratory**	Hydrogen tools portal, Hydrogen Safety Panel
Collaborator	**National Renewable Energy Laboratory**	Technical exchanges on QRA, safety codes and standards committees and task groups

Collaborations & Tech Transfer: HyRAM active users span stakeholder groups, applications, countries



Remaining challenges & barriers

- Science-Based Code Improvements
  - Incorporate validated physics models for hydrogen behaviors, including: liquid/cryogenic release behavior; deflagration (unconfined) and detonation models, flow/flame surface interactions, barrier walls, ignition, etc.
  - Generate data/probabilities for hydrogen system component failures, leak frequencies, detection effectiveness, etc. based on operating experience or other information
  - Consensus agreement on suitable means of quantifying hydrogen system mitigation features is not reached
- Hydrogen Tunnel Safety
  - Local AHJ permissions may not be granted, despite scientific analysis
  - Different jurisdictions grant differing permissions for FCEV, resulting in complicated use allowances

Proposed future work

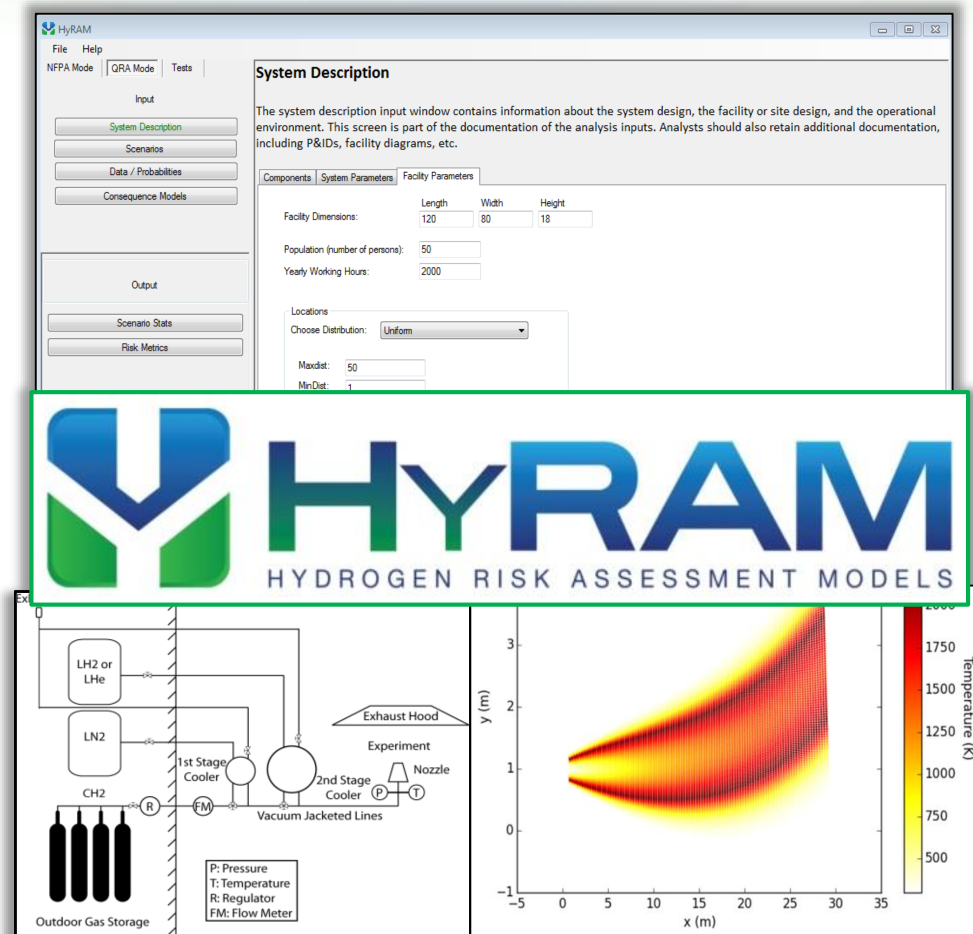
- Rest of FY19:
  - Refine characterization of LH2 releases with validated cold plume release and identify full scale modeling needs to provide sound scientific basis for revised bulk LH2 separation distances in NFPA 2/55.
  - Support alternate means permit for real-world LH2 refueling station
  - Support Federal Highway DOE/DOT collaboration with analysis and characterizations

- FY20:
  - Contribute to global hydrogen tunnel safety research through HyTunnel-CS
  - Develop risk framework for emerging H2@Scale Applications
  - Explore and develop non-destructive tank inspection methodologies to risk-inform the service life of hydrogen cylinders

- Any proposed future work is subject to change based on funding levels

Technology transfer activities

- Technology transfer strategies are tied to the accessibility of HyRAM QRA tool kit to other users (AHJs, station designers, etc.) to analyze station risks or consequences-only
- HyRAM moving to open source, which allows for more tech transfer through collaboration



Current release is version 2.0

Summary

- **Three-pronged R&D approach**
  - Provide science & engineering basis for assessing safety (risk) of H2 systems and facilitate use of that information in RCS and permitting
  - Coordinated activities ensures: Accelerated transfer of R&D results into codes and standards; R&D focused on high-impact stakeholder problems
- **Reducing barriers** related to limited availability and access to safety data for RCS revision
- **Technical Accomplishments:** Improvements to HyRAM QRA calculations for added flexibility
- **Progress:** Updating liquid separation distances by calculating leak frequencies; Alternative Means and Measures (AMM) report for real-world station; H_2 FCEV tunnel safety study
- **Future Work**: HyRAM 2.0 source code will be released to the public; develop and test cold plume model for LH2 releases

Technical Back-Up Slides

HyRAM: Making hydrogen safety science accessible through integrated tools

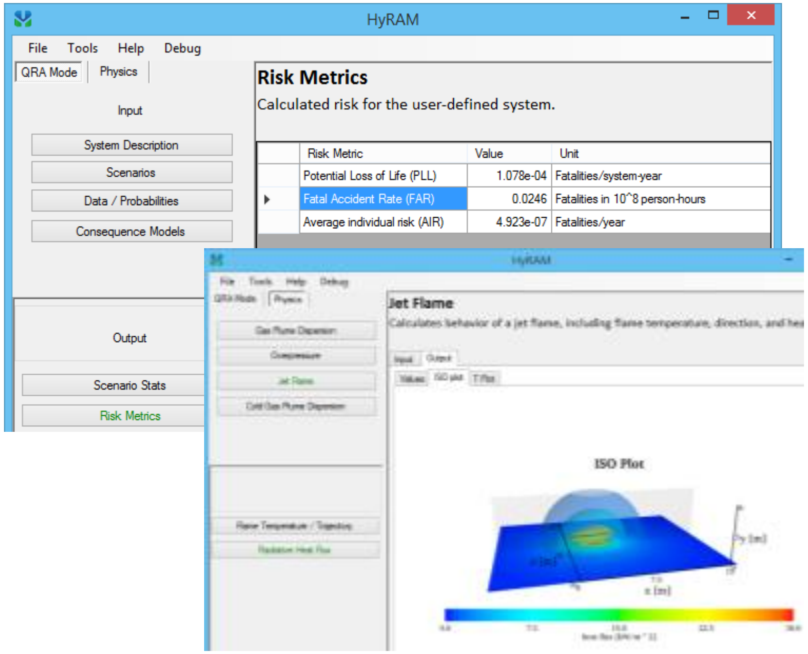
First-of-its-kind integration platform for state-of-the-art hydrogen safety models & data - **built to put the R&D into the hands of industry safety experts**

Core functionality:

- Quantitative risk assessment (QRA) methodology
- Frequency & probability data for hydrogen component failures
- Fast-running models of hydrogen gas and flame behaviors

Key features:

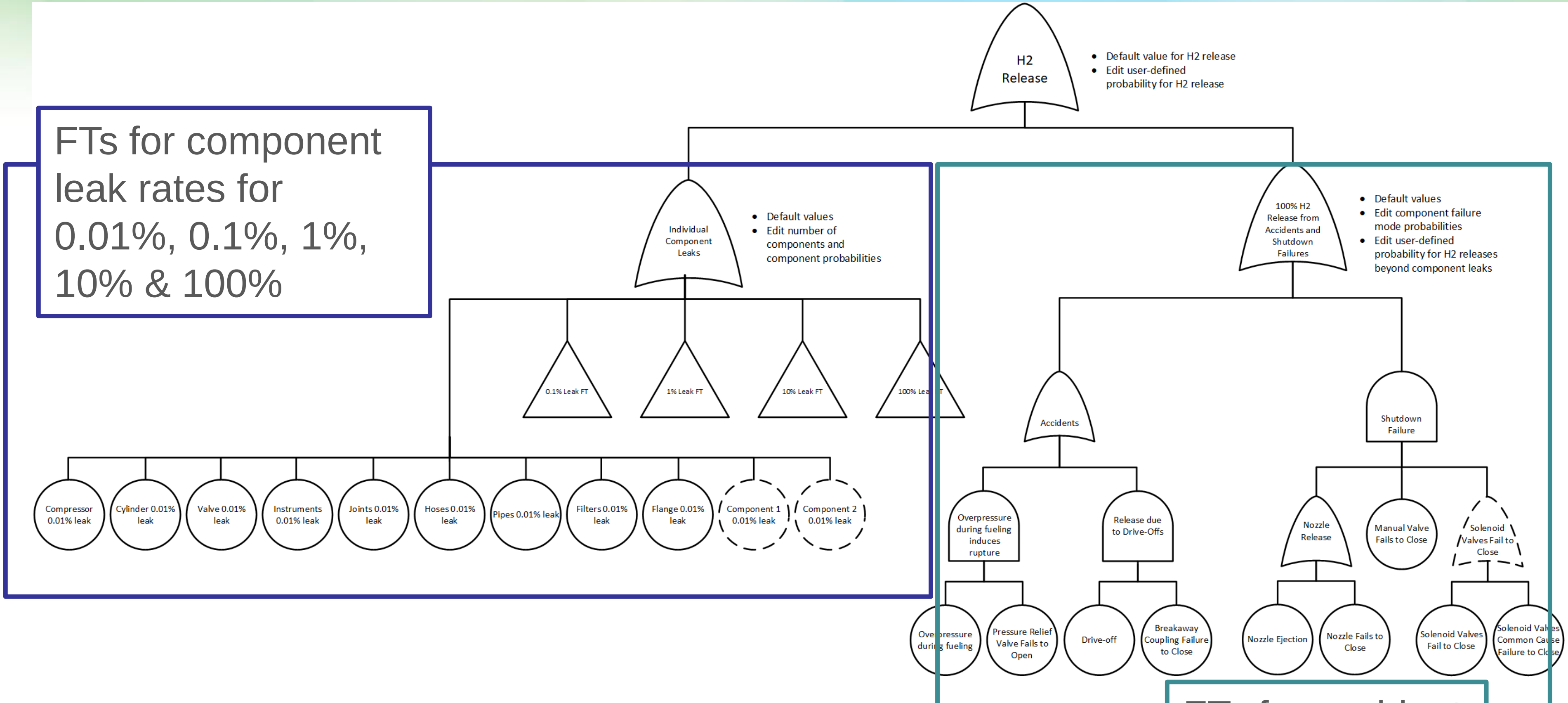
- GUI & Mathematics Middleware
- Documented approach, models, algorithms
- Flexible and expandable framework; supported by active R&D



Free download at http://hyram.sandia.gov

QRA Fault Trees (FT) Updates

FTs for component leak rates for 0.01%, 0.1%, 1%, 10% & 100%

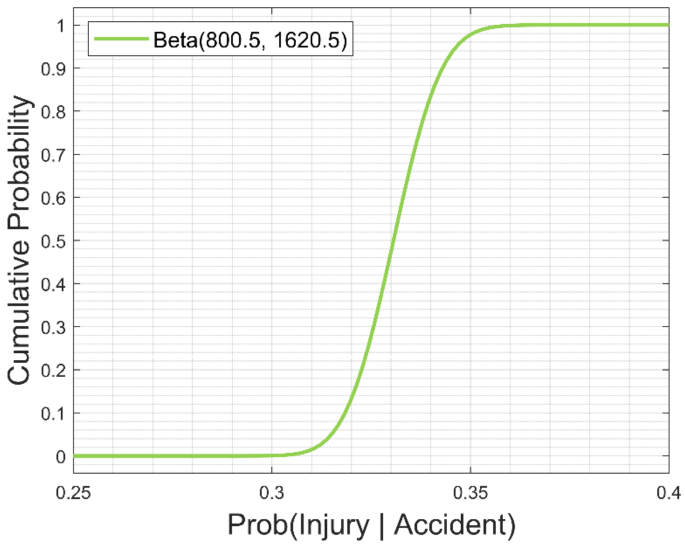


FTs for accident scenarios or shutdown failures

Current risk analysis contains static fault trees for one scenario. Customization will allow for risk analysis to be applied to unique H2 applications

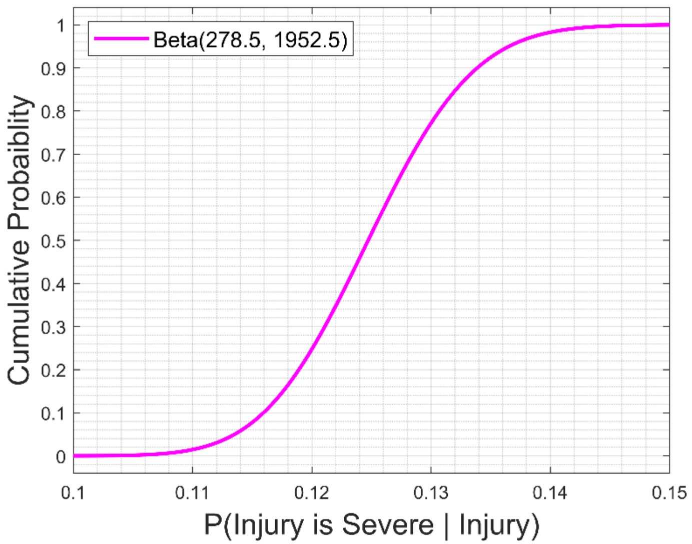
Uncertainty around scenario probabilities

Probability of injury given an accident



	Total Number of Accidents	Total Number of Injuries
Z-L Ma et al. (via Bassan)	116	35
Caliendo	2304	765

Probability that an accident is severe given that an injury occurred

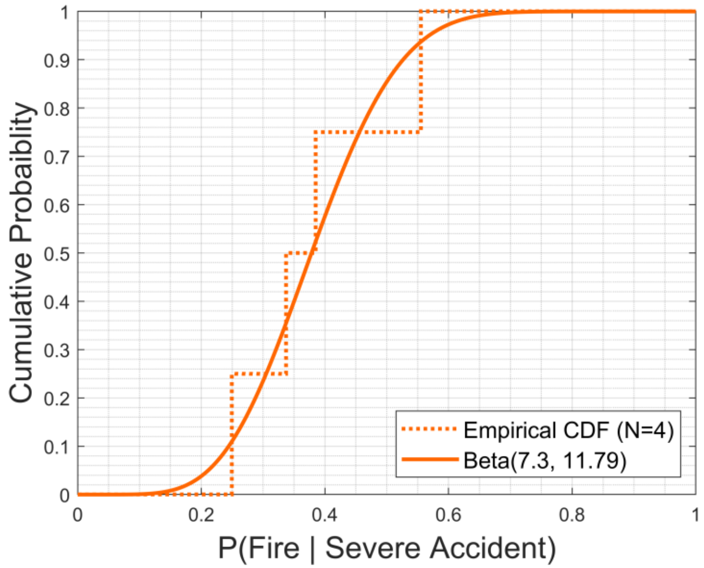


	Total Number of Injuries	Severe Injury (or fatality)
Amunsden	562	97
Amunsden	1130	125
Z-L Ma et al.	35	11
Meng Qu	503	45

Calculation of uncertainty allows a more complete range of answers to be characterized

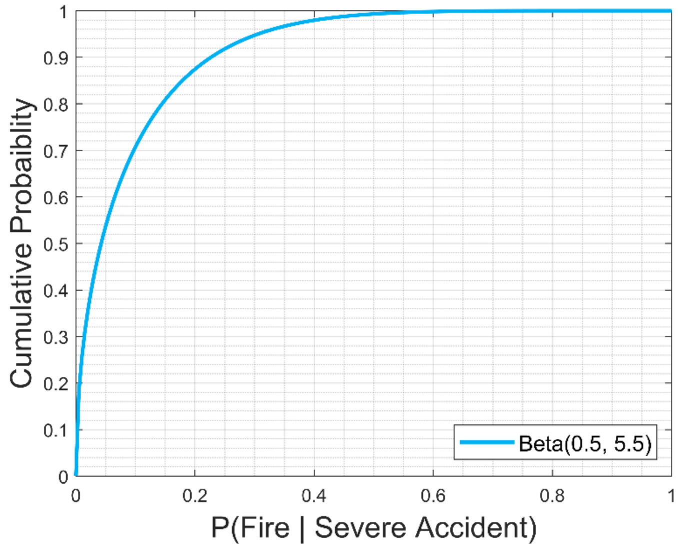
Uncertainty around scenario probabilities

Probability that a fire occurs given severe accident



Year:	2006	2007	2008	2009
Average Severe Crash Rates	0.2045	0.1608	0.0913	0.1284
Average Fire Crash Rates	0.0510	0.0619	0.0507	0.0433

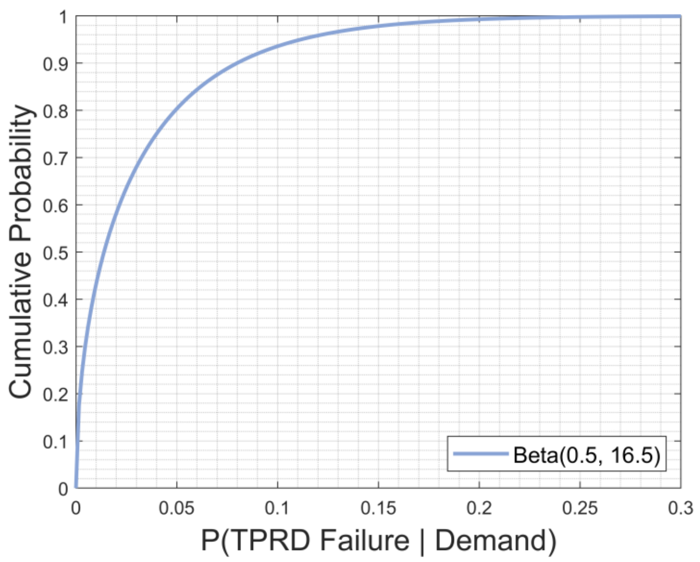
Probability of damage-induced H2 release



- Based on 5 experiments where no release occurred
- Beta distribution assumed along with Jeffrey's uninformed prior

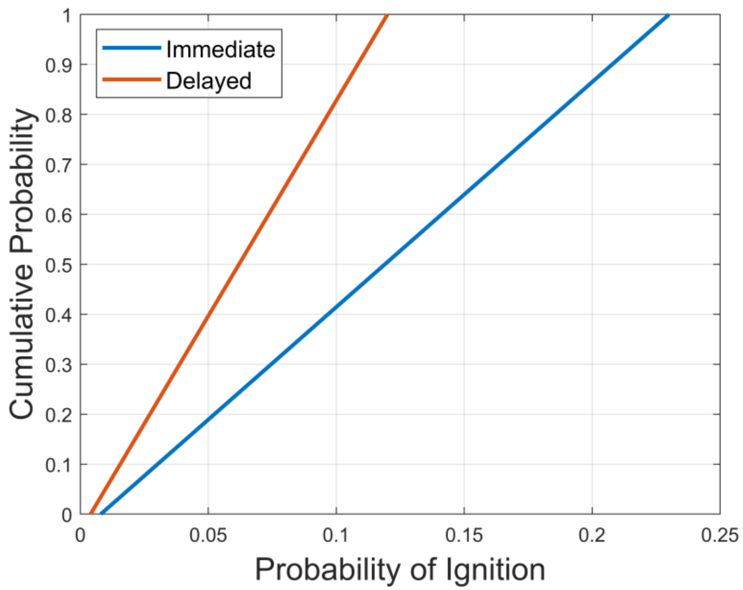
Uncertainty around scenario probabilities

Uncertainty of TPRD failure to operate



- Bayesian approach with informed prior
- Choice of an informed prior leads to a lower estimated probability of failure, but overall range where most of the distribution lies is similar to that obtained with a Jeffrey's prior

Probability of H2 ignition



- Due to wide range of ignition probability values, a uniform distribution between the lowest and highest values was chosen