SAND2020-4197D

Hydrogen Quantitative Risk Assessment

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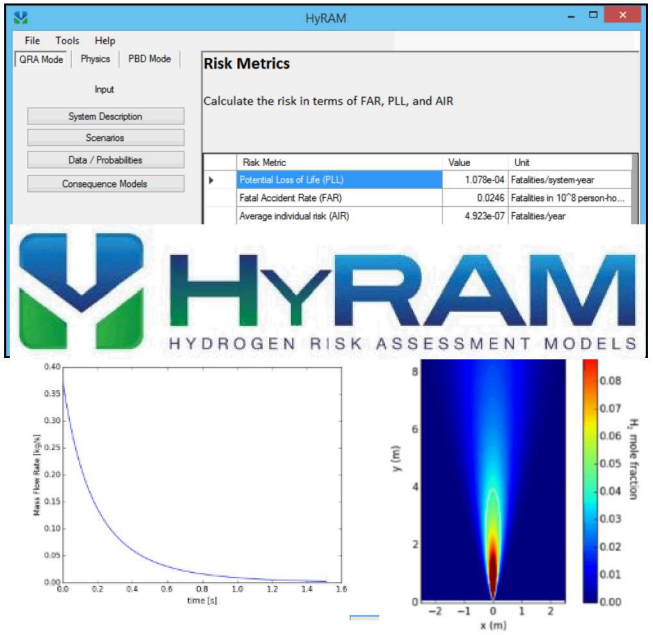
2020 DOE Hydrogen and Fuel Cells Annual Merit Review



Project # SCS011
SAND2020-XXXX

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Project start date: Oct. 2003
- Project end date: Sept. 2020*

  * Project continuation and direction determined by DOE annually.

Budget

- FY19 DOE Funding: $740K

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

Partners

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

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

International engagement:
IPHE

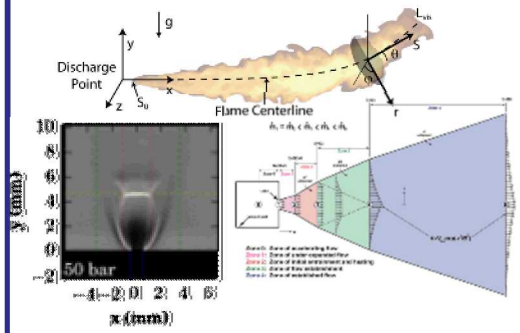
Relevance

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 and Impact
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.

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

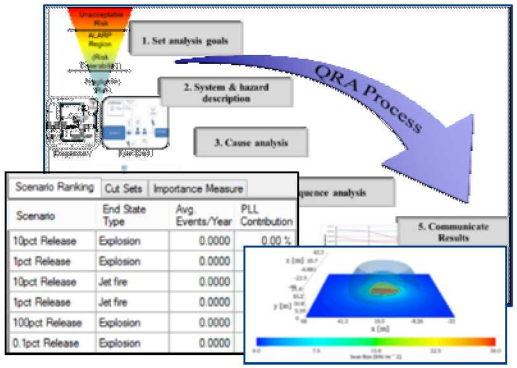
Behavior R&D



Develop and validate scientific models

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

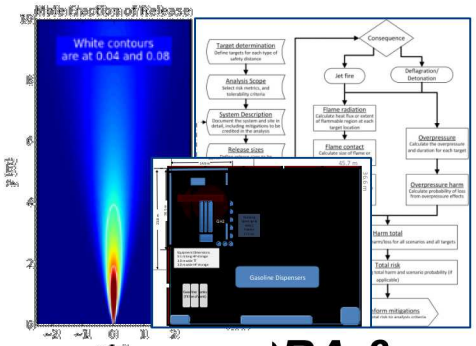
Risk R&D



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

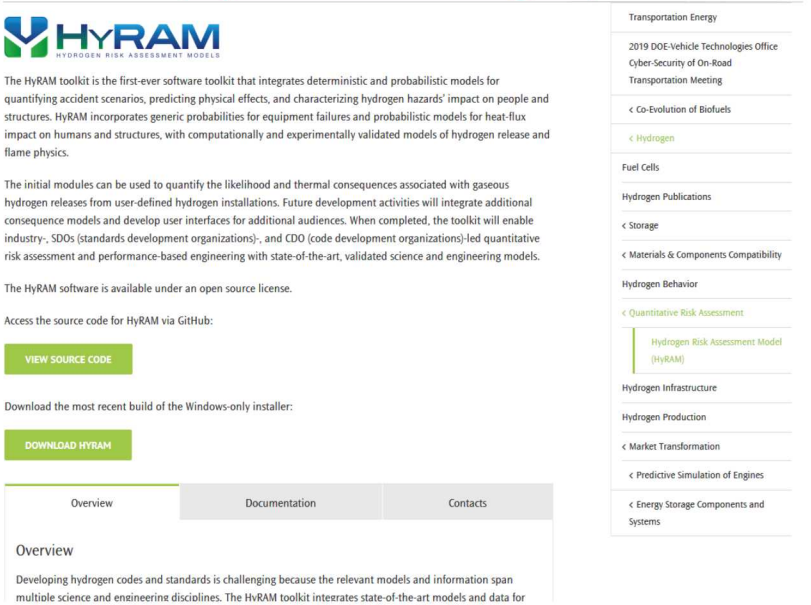
Approach: FY19-20 Milestones

Impact Areas	Status
Liquid Hydrogen QRA Methodology Development	
• Release HyRAM 2.0 as open source • Incorporate cold plume model into HyRAM • Develop LH2 leak frequencies and consequence modeling • Support NFPA 2/55 Task Group in developing code proposals	Complete (June 2019) On track (June 2020) On track (May 2020) Ongoing
Real-World Application of Alternative Means	
• Draft paper on alternative means & measures	Ongoing
Enabling Fuel Cell Electric Vehicles in Tunnels	
• Expand tunnel white paper to include other alternative-fuels • Work with federal highway, other stakeholders to address all US tunnels	Complete (April 2020) Ongoing
SCS Gap Identification for Rail Applications of Hydrogen Fuel Cells	
• Report identifying rail-specific SCS, best practices, and gaps for rail use	On track (Sept 2020)
Expansion of HyRAM QRA and Physics Models with Additional Capabilities	
• Collaborate with external partners to add natural gas and other models	Ongoing

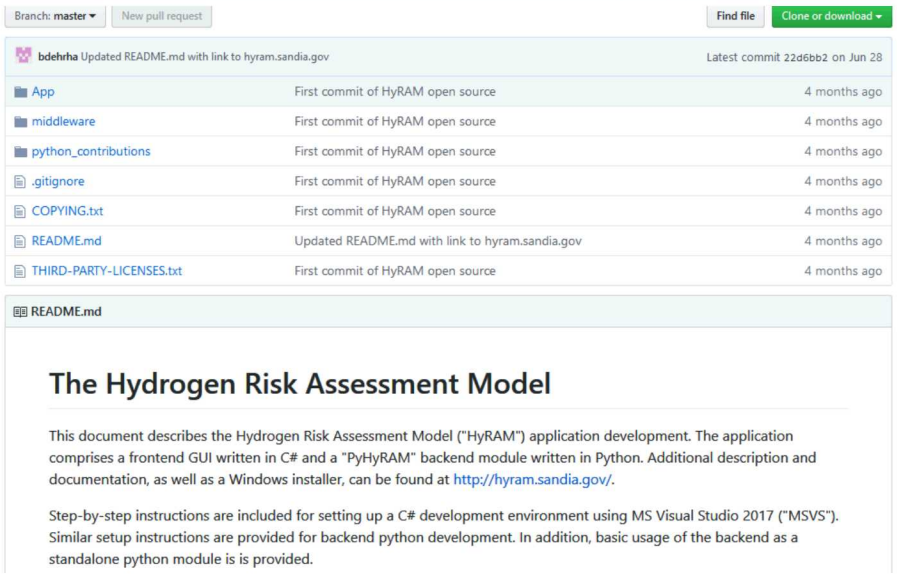
Accomplishment: Released HyRAM 2.0 as open source

- HyRAM 2.0 now an open-source software
  - Users have access to the source code
- HyRAM 2.0 can be installed on Windows using executable

hyram.sandia.gov



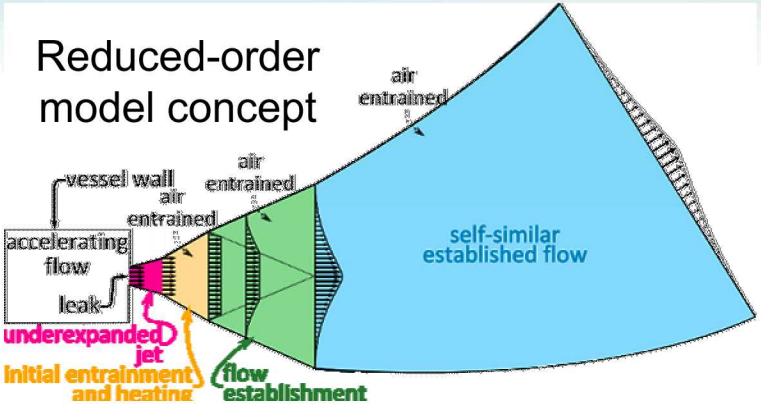
github.com/sandialabs/hyram

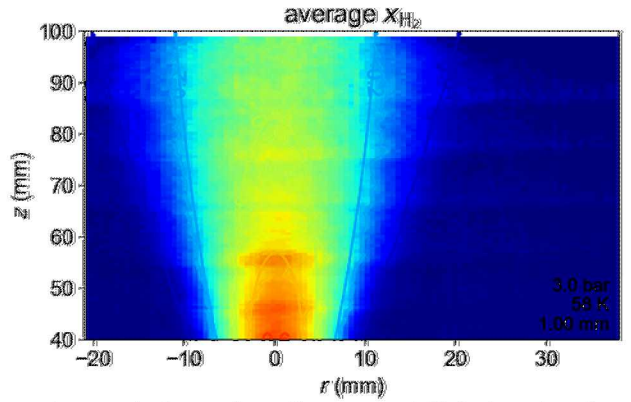


Giving users access to the source code and providing a free installer will encourage collaboration and future improvements

Progress: Incorporate ColdPlume into HyRAM

- Experimental work has validated cryogenic vapor release model at lab-scale, current work is scaling up to outdoor releases*
- Model accurately simulates mole fraction, temperature, and velocity - can be used as predictive tool
- Reduced-order model allows for wide usage and fast-running results





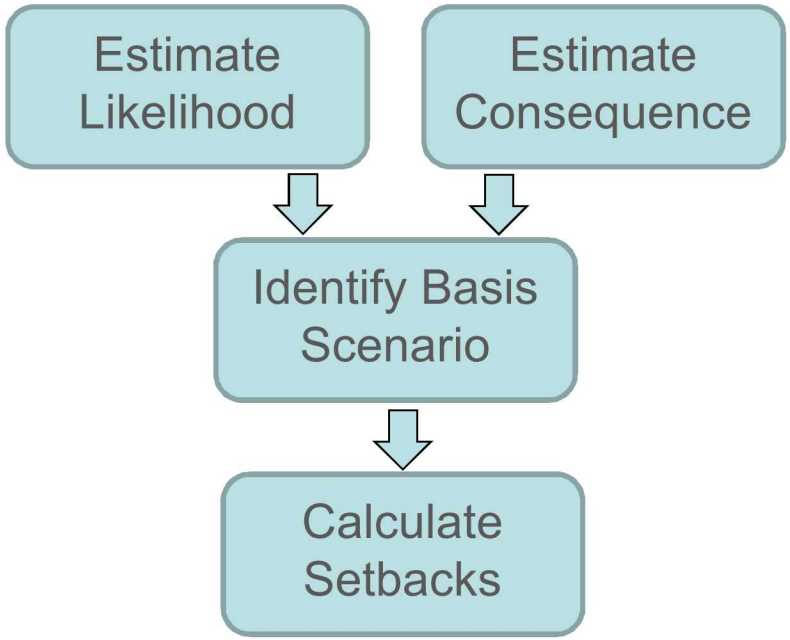
Experimental = shading and thick, dashed lines
ColdPlume Model = thin, solid lines

** See SCS010 for more details*

Public access through open source software allows for many different users access to validated models

Progress: Science-based liquid H_2 separation distances

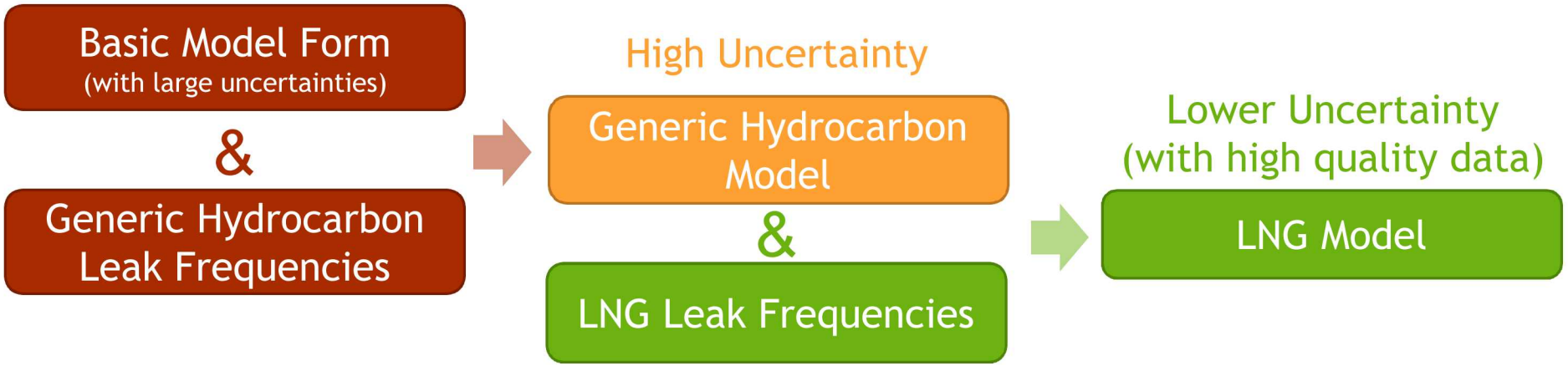
- Goal: Develop leak frequencies and other data needed to support the NFPA 2/55 separation distance task group
- Progress:
  - Regular bi-weekly meetings
  - LNG leak frequencies developed first
    - Will update with LH2 leak data from industry partners
  - LH2 release model being added to HyRAM
    - Will also be used to estimate consequences of leak
  - Computational fluid dynamics (CFD) model being developed to assess liquid pooling scenarios



Risk-informed code requirements based on risk-significant scenarios could enable more sites to readily accept hydrogen infrastructure

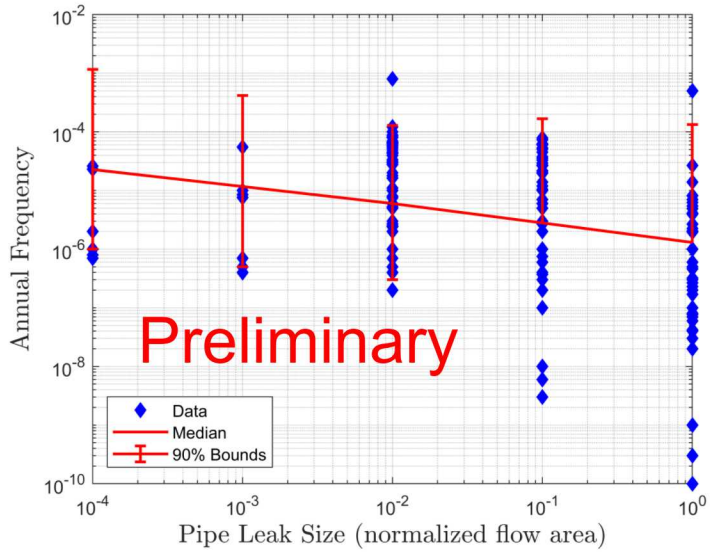
Progress: Leak frequency estimation using LNG

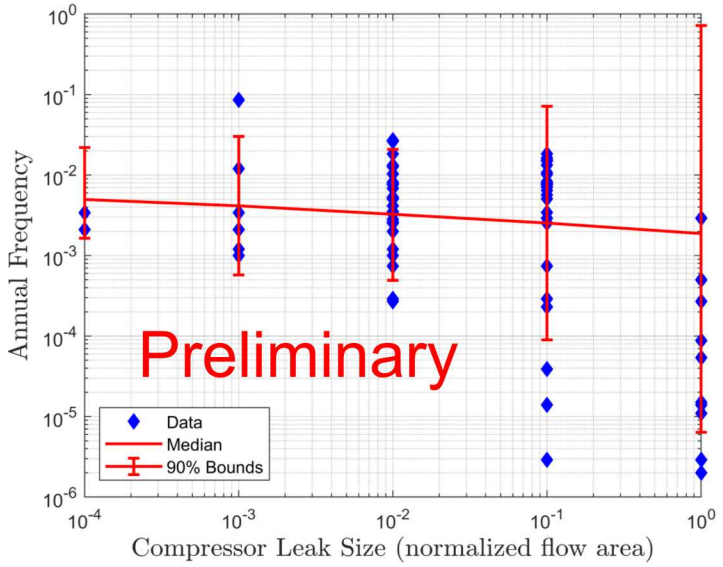
- Model update using Bayesian methods
  - Start with high uncertainty
  - Use generic hydrocarbon leak frequencies to refine the uncertainty (improve the model)
  - Incorporate LNG-specific leak frequencies to further refine the uncertainty
- Final model informed by generic and LNG data
  - If data is sparse, the model will predict a wide range of leak frequencies
  - If data is numerous and of high quality, the model will predict a narrower range of leak frequencies



Model can be readily updated with liquid hydrogen leak data provided by industry partners to improve the estimated leak frequencies

Progress: Preliminary LNG leak frequency results





- Underlying model is log-linear
- Uncertainty is high
- Median is the best measure of central tendency
- Generic hydrocarbon data is over-represented
- Use of both generic and LNG data may result in high uncertainty
  - If sufficient LNG data existed, the generic hydrocarbon data would not be used

Leak frequencies generated for different components and different leak sizes give flexibility in analysis

Accomplishment: Alternative fuel tunnel safety review

- Completed literature survey of hydrogen hazard and risk safety projects for tunnels
- Expanded document to include:
  - Traditional fuels
  - Battery-electric
  - Propane
  - Natural gas
- For each fuel:
  - Basic review of fuel properties
  - Identified any fuel-specific hazards
  - Identified relevant codes and standards
  - Reviewed experimental and simulation work in the literature
  - Identified gaps relevant for tunnels

Publicly available review of tunnel-relevant safety studies and prior work

Progress: SCS gap identification for rail

- Safety identified as main concern for all stakeholders for hydrogen for rail applications
  - From H2@Rail Workshop report (SAND2019-10191 R)
- Various systems to consider for hydrogen use on rail
  - Fuel (locomotive, tender car)
  - Cargo (tanker car)
  - Fueling/repair infrastructure
- Greatly increased fuel storage/usage requirements compared to light-duty vehicles
- Railroads exist in or nearby to all sorts of environments
  - Urban/rural, industrial/residential, transit/freight

Identifying rail-specific SCS gaps now can enable rail applications in the future

Responses to previous year reviewer's comments

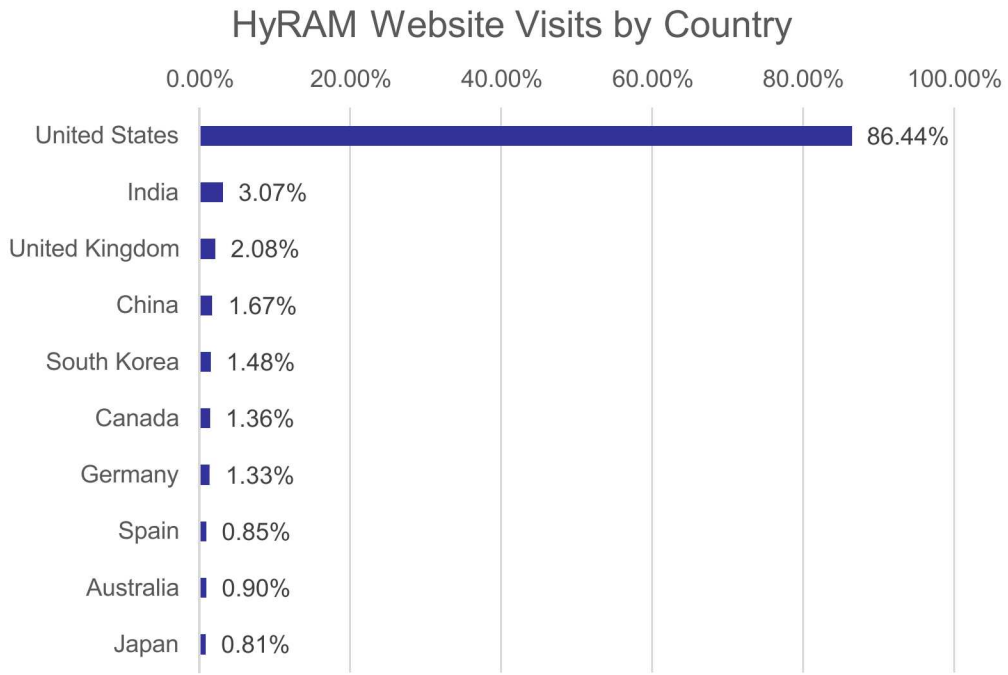
- ***Though it is not so much a weakness of the project as it is a resources issue, the LH2 experiments need to get completed in time to get the information to the NFPA 2 task force and get a proposal into the next version of NFPA 2.***
  - The project team is working closely with the NFPA 2 Task Group to provide risk-informed analysis in time for the code cycle, specifically for liquid hydrogen system leak frequencies and modeling using ColdPlume which will be released in HyRAM.
- ***The project team needs to address how systems developers can use existing data in HyRAM to address general scenarios involving other applications, systems, and components.***
  - The new User's Guide describes the QRA calculation inputs in more detail. The additional detail should provide better information about how the QRA calculations can be used for other applications.
- ***Some chosen physical effects models (e.g., for enclosure dispersion and overpressure) are limited to very specific boundary conditions, yet the models could be used beyond their original limiting parameters. Thus, it could be desirable to provide a warning to the user if the model is being used outside its validated range.***
  - The thermodynamics package for HyRAM has been revised, meaning that conditions (temperature and pressure) will have a much wider range of validity than before. Additionally, warnings have been improved and should be more useful for users.

Collaborations: Partners, RCS participation & international engagement

Relationship	Partner	Role
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)	**Air Liquide**, Industrial gas supplier	Research on LH2 releases and QRA
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

Since the latest version was uploaded on July 12, 2019, HyRAM has been **downloaded 930 times** (as of 3/18/20)



Remaining challenges & barriers

- Science-Based Code Improvements
  - Need data/probabilities for liquid hydrogen system component failures, leak frequencies, based on operating experience or other information
  - Liquid hydrogen pooling difficult to model without expensive CFD
  - Need better way to estimate overpressure without enclosure
- 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
- Additional Applications for Hydrogen
  - Different regulators oversee different parts of hydrogen production, storage, movement, and use
  - Safety-relevant properties of hydrogen blends with natural gas not clearly identified

Proposed future work

- Rest of FY20:
  - Provide support for sound scientific basis for revised bulk LH2 separation distances in NFPA 2/55 through leak frequency estimation and modeling
  - Support Federal Highway DOE/DOT collaboration with analysis and characterizations
  - Identify gaps in safety, codes, and standards for hydrogen rail applications
  - Develop a hydrogen energy jurisdiction map to cover all modes of transport and utilization
  - Review how hydrogen/natural gas blends might behave when released from a system, for possible future incorporation into HyRAM
- FY21:
  - Develop a free-plume delayed-ignition overpressure model and incorporate into HyRAM
- Any proposed future work is subject to change based on funding levels

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:** Release HyRAM 2.0 as open source, published alternative fuel vehicle tunnel safety literature review report
- **Progress:** ColdPlume model being incorporated into HyRAM; leak frequencies of LH2 estimated using LNG proxy; gap identification for rail underway
- **Future Work**: Support NFPA 55/2 Task Group for revised LH2 separation distances; support DOT collaboration for tunnels; identify gaps in SCS for rail; develop H2 jurisdiction map; identify H2/NG blend leak behavior literature

Technical Back-Up Slides

HyRAM: Making hydrogen safety science accessible through integrated tools

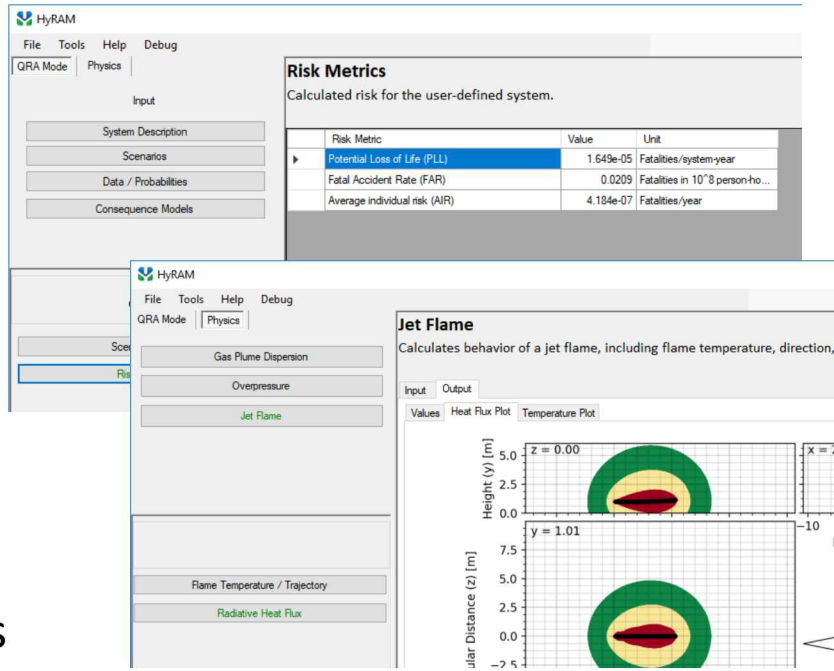
First-of-its-kind integration platform for state-of-the-art hydrogen safety models & data - **built to put the R&D into the hands of industry safety experts**

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

Reviewer-Only Slides

Critical Assumptions and Issues

- Issue: Multiple codes and standards and many individual requirements. Consensus involves multiple analyses, iterations, negotiations; repeated every code cycle
  - Assumption: Building tools to enable industry-, SDO/CDO-led QRA and consequence modeling directly impacts H_2 safety/infrastructure deployment
- Issue: AHJ does not accept risk and consequence analysis for real world application
  - Potential Solution: Continued education and outreach on hydrogen systems and efficacy of safety features
- Issue: Previous risk analyses identified jet flames as more likely, but recent events had delayed-ignition overpressure
  - Potential Solution: Explore ignition behavior/probability in more detail, develop tools to estimate effects of delayed-ignition overpressure

Presentations and Publications (Apr '19 – Apr '20)

Publications

- A.B. Muna, B.D. Ehrhart "Identification of Hydrogen Material Risk Research Areas" Sandia National Laboratories Report SAND2019-4458 (April 2019)
- G. Feliciano Morales, B.D. Ehrhart, A.B. Muna "HyRAM V2.0 User Guide" Sandia National Laboratories Report SAND2019-8940 (July 2019)
- B.D. Ehrhart, D.M. Brooks, A.B. Muna, C.B. LaFleur "Risk Assessment of Hydrogen Fuel Cell Electric Vehicles in Tunnels" Fire Technology **56**, 891-912 (2020)

Presentations

- C. LaFleur "Tunnel Scenario Estimation & Discussion" Codes & Standards Technical Team (July 11, 2019)
- C. LaFleur, B. Ehrhart, D. Brooks, A. Muna "Tunnel Scenario Estimation & Discussion" International Conference on Hydrogen Safety (ICHS) 2019, Adelaide, South Australia (September 24-26, 2019)
- B. Ehrhart, C. LaFleur, E. Hecht, M. Blaylock "Overview and Recent Developments for the Hydrogen Risk Assessment Models (HyRAM) Toolkit" 2019 Conference on Hydrogen Safety, Sacramento, CA (October 14-15, 2019)
- E.S. Hecht, A.B. Muna, B.D. Ehrhart, C. LaFleur "Hydrogen Risk Assessment Models 2.0: An open source quantitative risk assessment framework" Fuel Cell Seminar and Energy Exposition, Long Beach CA (November 5-7, 2019)
- B.D. Ehrhart, E.S. Hecht, A.B. Muna, C.B. LaFleur "Hydrogen Risk Assessment Models 2.0: Open-source quantitative risk assessment framework" Fuel Cell Technologies Office Webinar (January 28, 2020)

Additional References available in SCS010 & previous AMRs for SCS010, 011, 025