

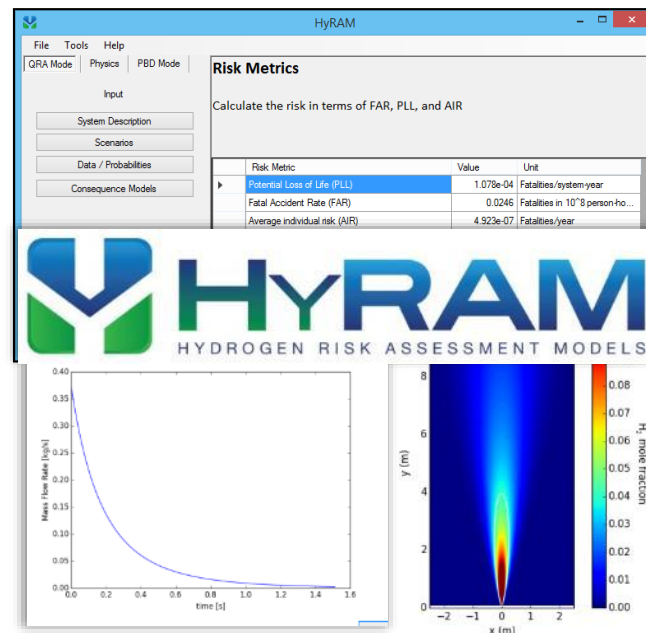
# Hydrogen Quantitative Risk Assessment

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*Sandia National Laboratories*

**Project Team: Chris LaFleur, Ethan Hecht, Dusty Brooks, Alice Muna, Myra Blaylock, Gabriela Bran Anleu, Cianan Sims (SI)**

*2020 DOE Hydrogen and Fuel Cells Annual Merit Review*



**Project # SCS011  
SAND2020-4197 D**

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# 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

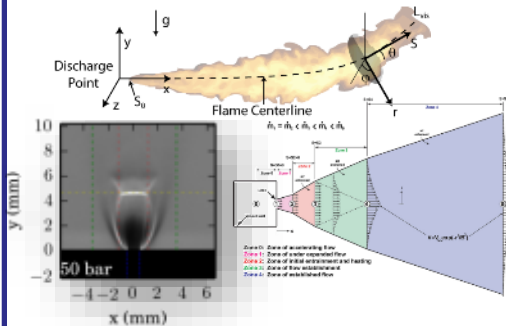
# Relevance

Objective: Develop a rigorous **scientific & engineering basis** for assessing safety risk of H<sub>2</sub> 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 H <sub>2</sub> 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 <sub>2</sub> -specific QRA tools & methods which support SCS decisions.
K. No Consistent Codification Plan and Process for Synchronization of R&D and Code Development	Apply H <sub>2</sub> -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.

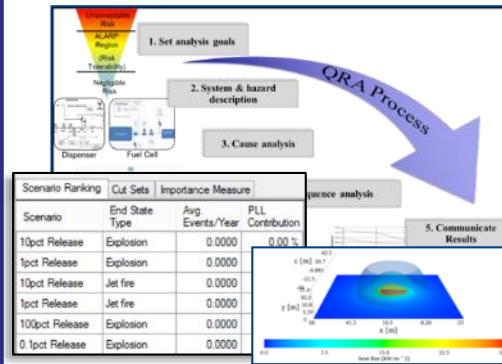
# Approach: *Coordinated activities* to enable consistent, rigorous, and accepted safety analysis

## Behavior R&D



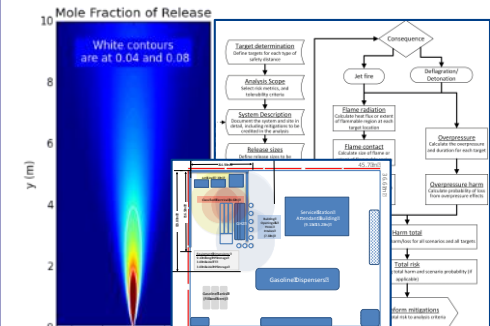
**Develop and validate scientific models** to accurately predict hazards and harm from liquid releases, flames, etc.

## 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<sub>2</sub> safety & SCS

# Approach: FY19-20 Milestones

Impact Areas	Status
<b>Liquid Hydrogen QRA Methodology Development</b>	
<ul style="list-style-type: none"> <li>• Release HyRAM 2.0 as open source</li> <li>• Incorporate cold plume model into HyRAM</li> <li>• Develop LH2 leak frequencies and consequence modeling</li> <li>• Support NFPA 2/55 Task Group in developing code proposals</li> </ul>	Complete (June 2019) On track (June 2020) On track (May 2020) Ongoing
<b>Real-World Application of Alternative Means</b>	
<ul style="list-style-type: none"> <li>• Draft paper on alternative means &amp; measures</li> </ul>	Ongoing
<b>Enabling Fuel Cell Electric Vehicles in Tunnels</b>	
<ul style="list-style-type: none"> <li>• Expand tunnel white paper to include other alternative-fuels</li> <li>• Work with federal highway, other stakeholders to address all US tunnels</li> </ul>	Complete (April 2020) Ongoing
<b>SCS Gap Identification for Rail Applications of Hydrogen Fuel Cells</b>	
<ul style="list-style-type: none"> <li>• Report identifying rail-specific SCS, best practices, and gaps for rail use</li> </ul>	On track (Sept 2020)
<b>Expansion of HyRAM QRA and Physics Models with Additional Capabilities</b>	
<ul style="list-style-type: none"> <li>• Collaborate with external partners to add natural gas and other models</li> </ul>	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](http://hyram.sandia.gov)



The HyRAM toolkit is the first-ever software toolkit that integrates deterministic and probabilistic models for quantifying accident scenarios, predicting physical effects, and characterizing hydrogen hazards' impact on people and structures. HyRAM incorporates generic probabilities for equipment failures and probabilistic models for heat-flux impact on humans and structures, with computationally and experimentally validated models of hydrogen release and flame physics.

The initial modules can be used to quantify the likelihood and thermal consequences associated with gaseous hydrogen releases from user-defined hydrogen installations. Future development activities will integrate additional consequence models and develop user interfaces for additional audiences. When completed, the toolkit will enable industry, SDOs (standards development organizations), and CDO (code development organizations)-led quantitative risk assessment and performance-based engineering with state-of-the-art, validated science and engineering models.

The HyRAM software is available under an open source license.

Access the source code for HyRAM via GitHub:

[VIEW SOURCE CODE](#)

Download the most recent build of the Windows-only installer:

[DOWNLOAD HYRAM](#)

Overview	Documentation	Contacts
<p>Overview</p> <p>Developing hydrogen codes and standards is challenging because the relevant models and information span multiple science and engineering disciplines. The HyRAM toolkit integrates state-of-the-art models and data for</p>		

Transportation Energy
2019 DOE Vehicle Technologies Office Cyber-Security of On-Road Transportation Meeting
< Co-Evolution of Biofuels
< Hydrogen
Fuel Cells
Hydrogen Publications
< Storage
< Materials & Components Compatibility
Hydrogen Behavior
< Quantitative Risk Assessment
Hydrogen Risk Assessment Model (HyRAM)
Hydrogen Infrastructure
Hydrogen Production
< Market Transformation
< Predictive Simulation of Engines
< Energy Storage Components and Systems

[github.com/sandia-labs/hyram](https://github.com/sandia-labs/hyram)

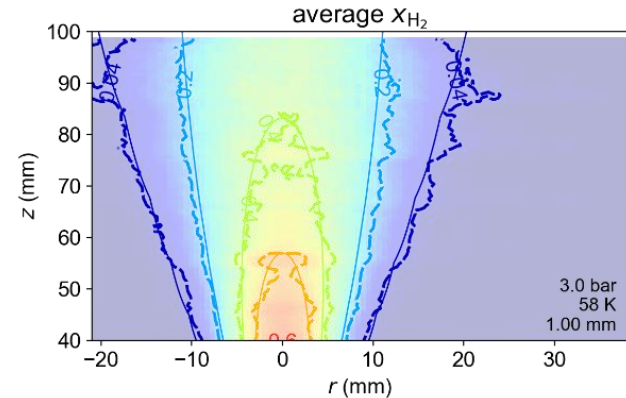
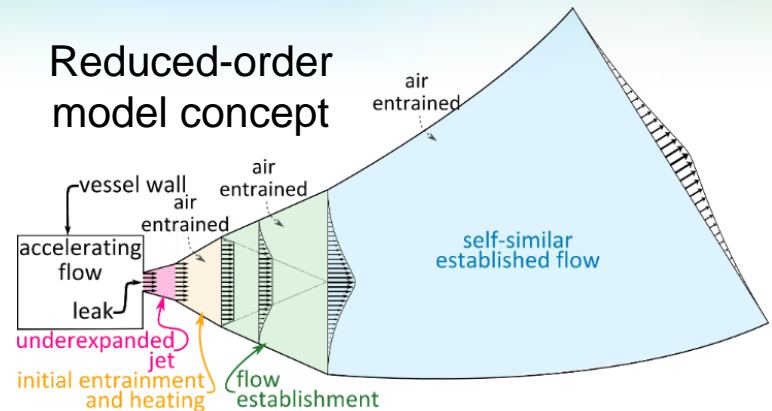
Branch: master	New pull request	Find file	Clone or download
bdehrha Updated README.md with link to hyram.sandia.gov Latest commit 22d6bb2 on Jun 28			
App	First commit of HyRAM open source		4 months ago
middleware	First commit of HyRAM open source		4 months ago
python_contributions	First commit of HyRAM open source		4 months ago
.gitignore	First commit of HyRAM open source		4 months ago
COPYING.txt	First commit of HyRAM open source		4 months ago
README.md	Updated README.md with link to hyram.sandia.gov		4 months ago
THIRD-PARTY-LICENSES.txt	First commit of HyRAM open source		4 months ago

README.md
<h2>The Hydrogen Risk Assessment Model</h2> <p>This document describes the Hydrogen Risk Assessment Model ("HyRAM") application development. The application comprises a frontend GUI written in C# and a "PyHyRAM" backend module written in Python. Additional description and documentation, as well as a Windows installer, can be found at <a href="http://hyram.sandia.gov/">http://hyram.sandia.gov/</a>.</p> <p>Step-by-step instructions are included for setting up a C# development environment using MS Visual Studio 2017 ("MSVS"). Similar setup instructions are provided for backend python development. In addition, basic usage of the backend as a standalone python module is provided.</p>

**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



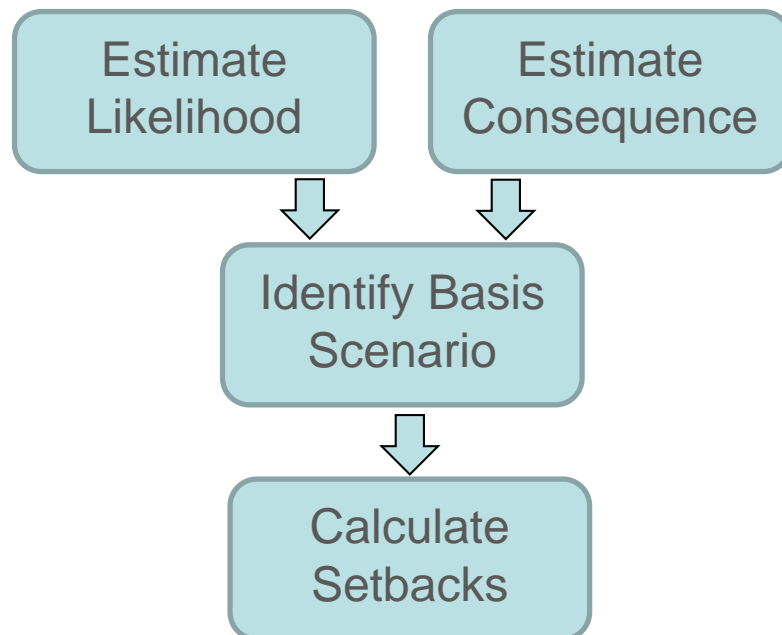
Experimental = shading and thick, dashed lines  
ColdPlume Model = thin, solid lines

\* 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<sub>2</sub> 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

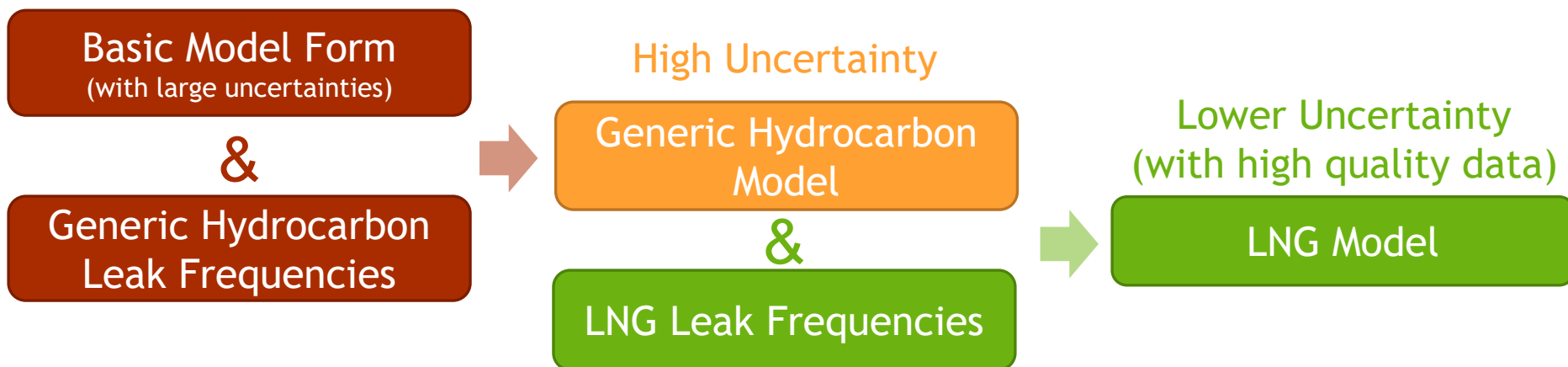


Risk-informed code requirements based on risk-significant scenarios could enable more sites to readily accept hydrogen infrastructure



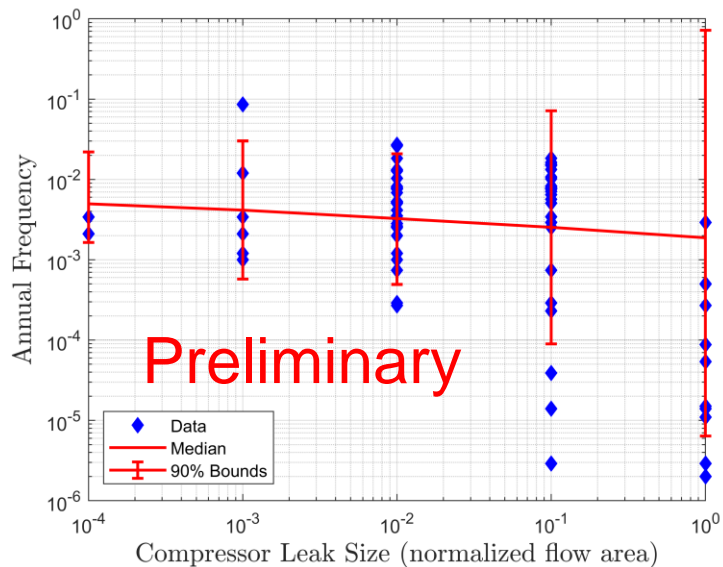
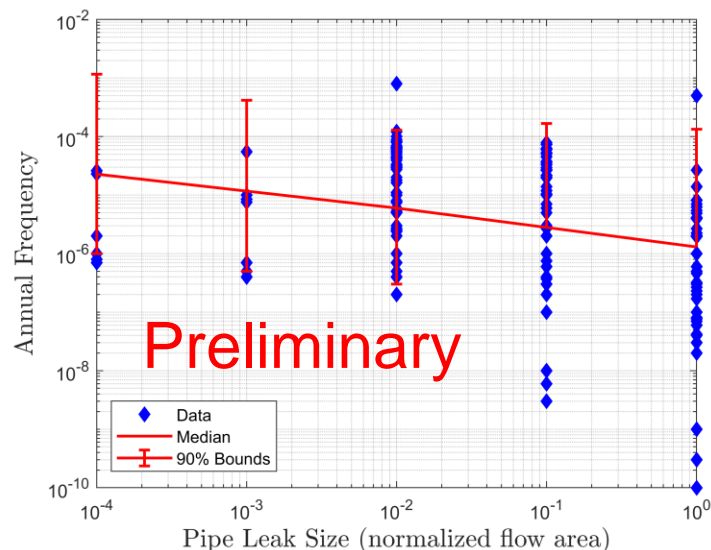
# Progress: Leak frequency estimation using LNG

- 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

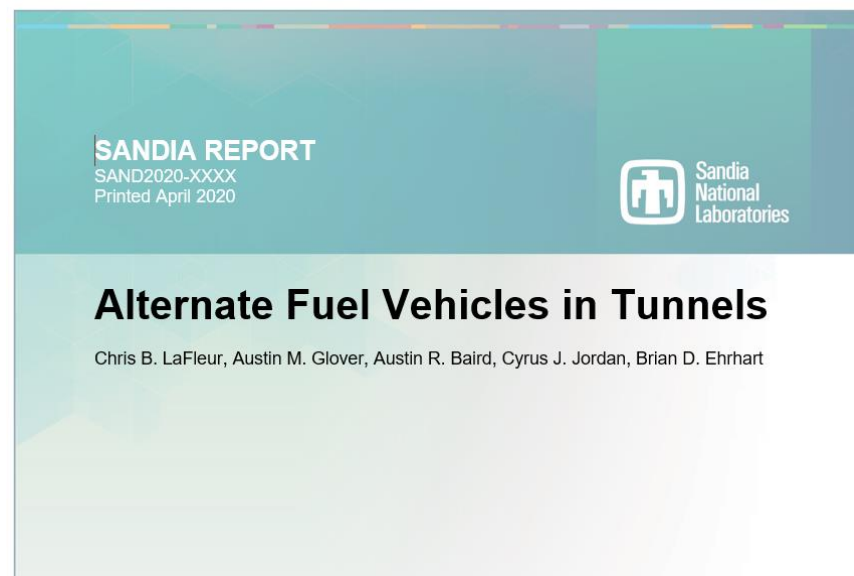


- Underlying model is log-linear
- Uncertainty is high
- Median is the best measure of central tendency
- Generic hydrocarbon data is over-represented
- Use of both generic and LNG data may result in high uncertainty
  - If sufficient LNG data existed, the generic hydrocarbon data would not be used

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

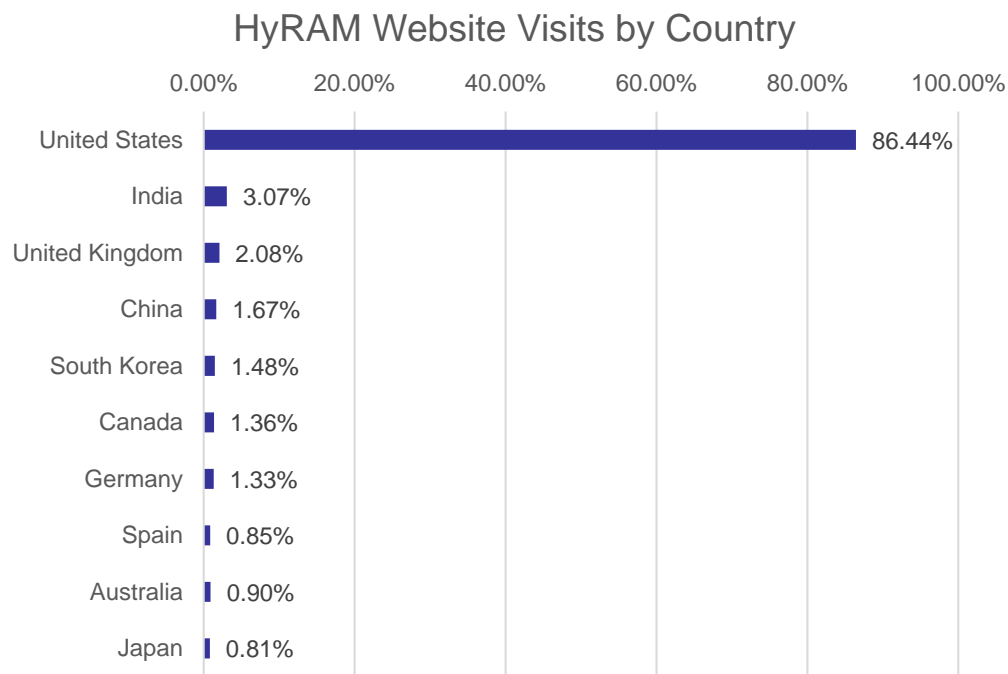
- ***Though it is not so much a weakness of the project as it is a resources issue, the LH2 experiments need to get completed in time to get the information to the NFPA 2 task force and get a proposal into the next version of NFPA 2.***
  - The project team is working closely with the NFPA 2 Task Group 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)	<b>FirstElement Fuel</b> , Station Developer	In-kind support, data exchange for QRA tool, PBD activities
CRADA (Signed)	<b>Frontier Energy</b> , (Manager of the California Fuel Cell Partnership)	Develop industry stakeholders in support of LH2 Behavior Characterization
CRADA (Signed)	<b>Air Liquide</b> , Industrial gas supplier	Research on LH2 releases and QRA
Code Committee Members	<b>NFPA 2, 55</b>	Separation distances task group, enclosures task group, and permitting task group.
Collaborator	<b>Pacific Northwest National Laboratory</b>	Hydrogen tools portal, Hydrogen Safety Panel
Collaborator	<b>National Renewable Energy Laboratory</b>	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 H<sub>2</sub> 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 LH<sub>2</sub> estimated using LNG proxy; gap identification for rail underway
- **Future Work:** Support NFPA 55/2 Task Group for revised LH<sub>2</sub> separation distances; support DOT collaboration for tunnels; identify gaps in SCS for rail; develop H<sub>2</sub> jurisdiction map; identify H<sub>2</sub>/NG blend leak behavior literature

# Technical Back-Up Slides

# HyRAM: Making hydrogen safety science accessible through integrated tools

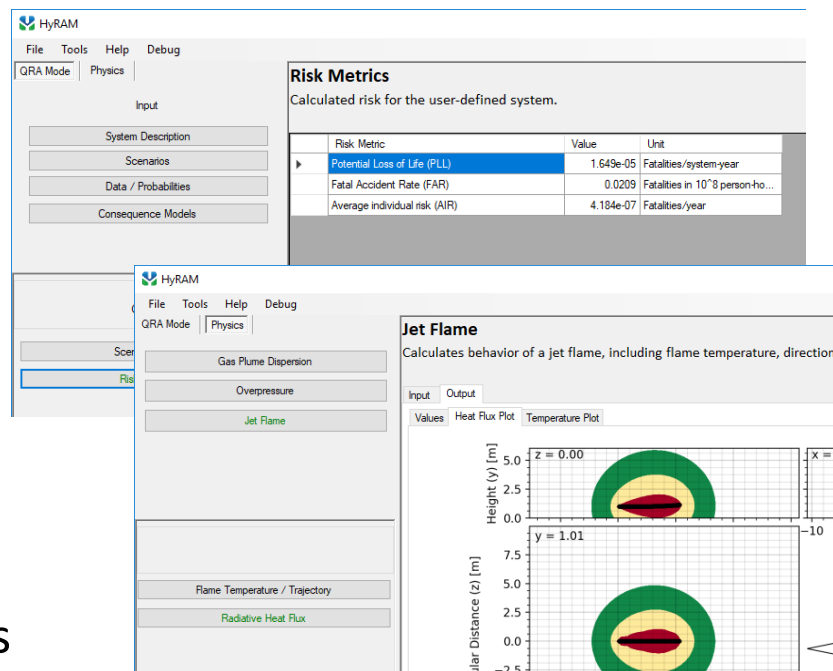
First-of-its-kind integration platform for state-of-the-art hydrogen safety models & data - built to put the R&D into the hands of industry safety experts

## 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://hynam.sandia.gov>