



SAND2021-4471PE

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Hydrogen Quantitative Risk Assessment

SCS011 – AOP 6.2.0.801

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2021 DOE Hydrogen Program Annual Merit Review and Peer Evaluation Meeting (AMR)

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Project Goal

Develop a rigorous **scientific & engineering** basis for assessing safety risk of H2 systems and **facilitate the use of that information** for revising safety regulations, codes, and standards (RCS) for emerging hydrogen technologies.

- Address significant issues relevant to code requirements through the consistent, logical, and science-based use of QRA and other risk-informed approaches
- Create and maintain reduced-order models and tools in an integrated framework (HyRAM) to support a safer deployment of new hydrogen technologies
- Generate new data and advance risk-informed approaches needed to evaluate emerging H2@Scale applications
- Demonstrate leadership in the international harmonization of standards for LH2 and hydrogen infrastructure, including tunnels



Overview

Timeline

Project start date: Oct. 2003

Project end date: Sept. 2021*

* Project continuation and direction determined by DOE annually

Budget

FY20 DOE Funding: \$750k

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, Air Liquide, Quong & Associates, PNNL, NREL, ANL, HySafe, 40+ organizations using HyRAM

SDO/CDO participation:

- NFPA 2/55, DOT Tunnel Jurisdictions, CaFCP

International engagement:

- IPHE, IEC



Relevance

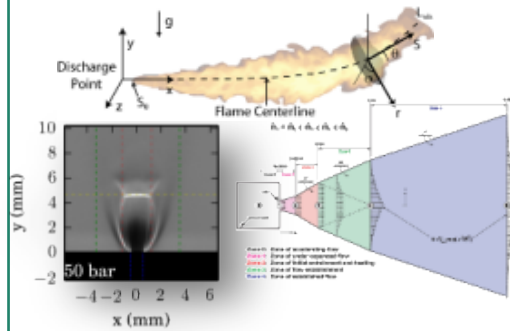
Goal: Develop a rigorous **scientific & engineering** basis for assessing safety risk of H2 systems and **facilitate the use of that information** for revising safety RCS for emerging hydrogen technologies.

Barrier from 2015 SCS MYRDD	Project 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 H₂-specific QRA tools, data , & methods which support SCS requirements.
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

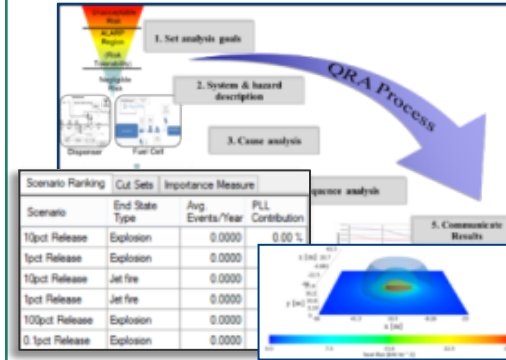
Behavior R&D



Develop and validate scientific models

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

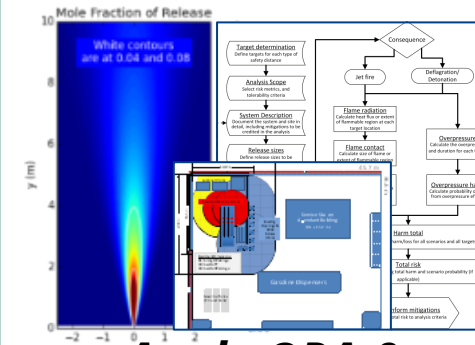
Risk R&D



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 H₂ safety codes and standards



Approach: FY20-21 Milestones

Impact Areas	Status
Liquid Hydrogen QRA Methodology Development	
<ul style="list-style-type: none">• Release HyRAM 3.0 with capability for liquid releases• Develop LH2 leak frequencies and consequence modeling• Support NFPA 2/55 Task Groups in analyzing scenarios	Complete (Sept 2020) On track (May 2021) Ongoing
Enabling Fuel Cell Electric Vehicles in Tunnels	
<ul style="list-style-type: none">• Work with FHWA, other stakeholders to address all US tunnels	Ongoing
SCS Gap Identification for Rail Applications of Hydrogen Fuel Cells	
<ul style="list-style-type: none">• Identify rail-specific SCS gaps and best practices	On track (Sept 2021)
Identifying Federal Oversight for H2@Scale	
<ul style="list-style-type: none">• Publish regulatory map identifying federal oversight of H2 systems	Complete (March 2021)
Expansion of HyRAM Models with Additional Capabilities	
<ul style="list-style-type: none">• Collaborate with external partners to add natural gas (methane) and propane to software• Identify experimental data in literature for releases H2/NG blends for future inclusion in HyRAM• Add unconfined overpressure model to HyRAM QRA and Physics	On track (Sept 2021) On track (Sept 2021) On track (Sept 2021)



Accomplishment: Capability to Simulate Cryogenic Plumes Added to HyRAM 3.0

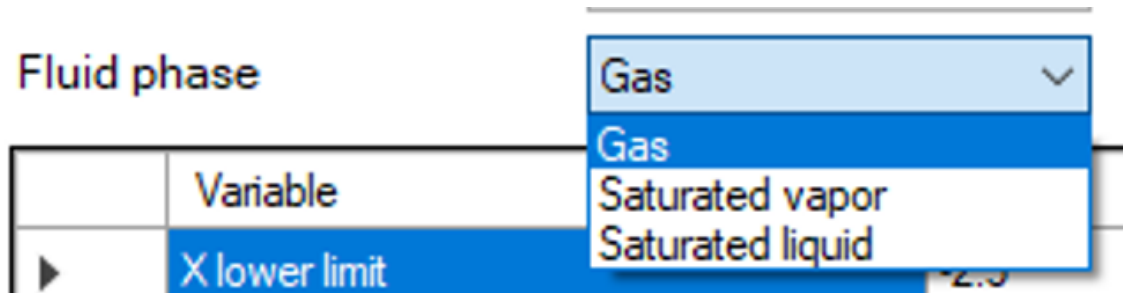
Experimental work has validated cryogenic vapor release model at lab-scale, current work has scaled up to outdoor releases*

Incorporated into QRA and Physics models

- Unignited plume, jet fire, accumulation in enclosure
- No LH2-specific default leak frequencies for QRA yet, but user-editable

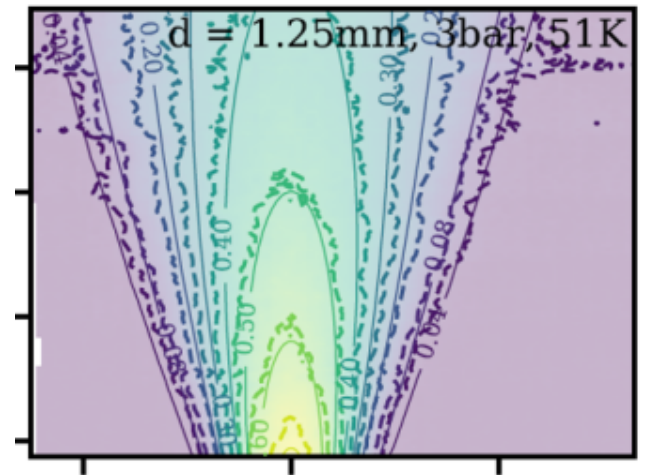
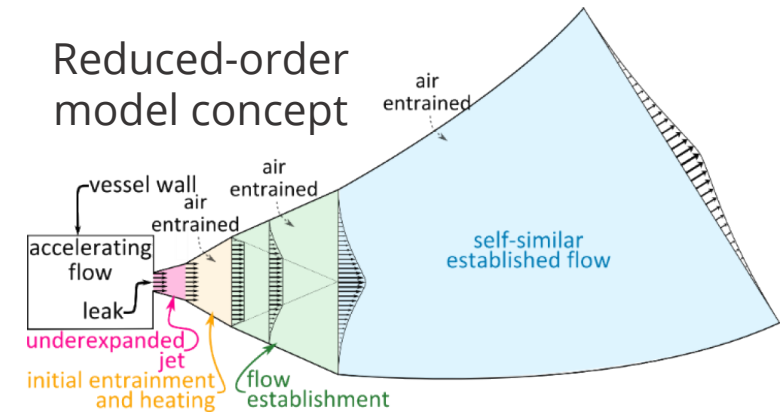
Free and open-source software: <https://hynam.sandia.gov>

HyRAM
Graphical User
Interface



* See SCS010
for more details

Users can now use simulations of cryogenic fluid leaks in risk assessments and codes & standards revisions



Experimental = shading and thick, dashed lines
HyRAM Model = thin, solid lines
Axis ticks are 20 mm



Accomplishment: HyRAM Validation Study

Addition of cryogenic release model resulted in change to real gas equation of state

- HyRAM 3 compared to HyRAM 2
- Both compared to **literature data**

Literature data sets are from **multiple groups** and **all HyRAM physics models**

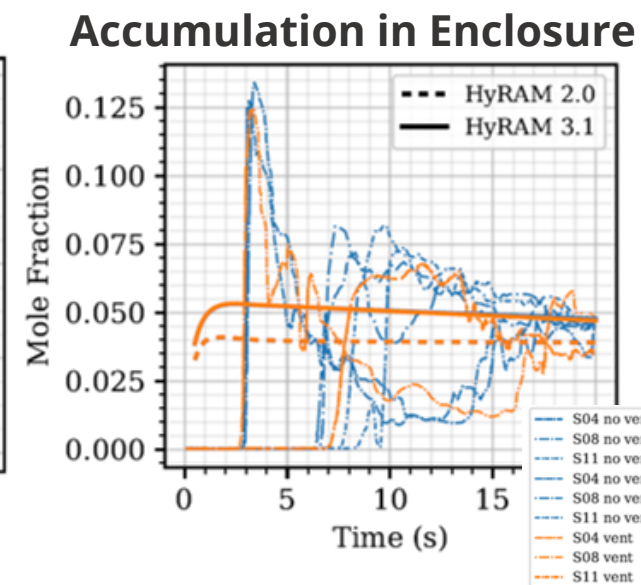
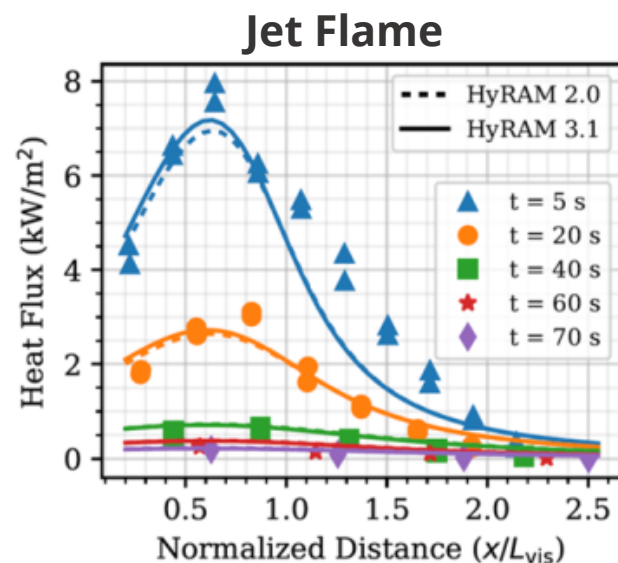
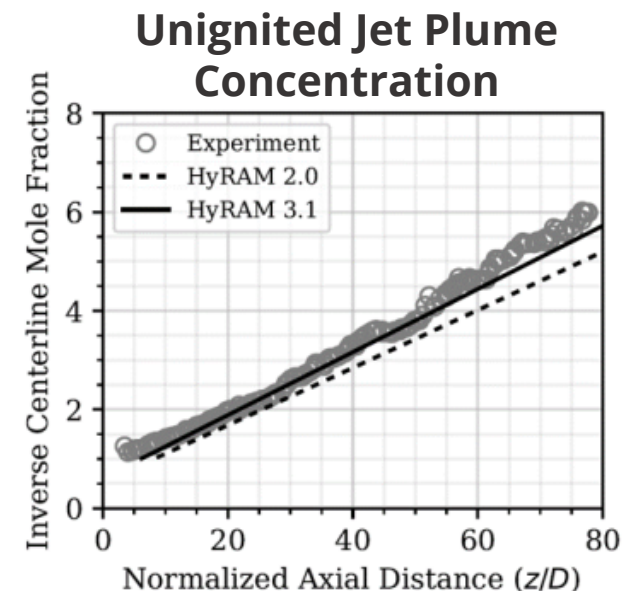
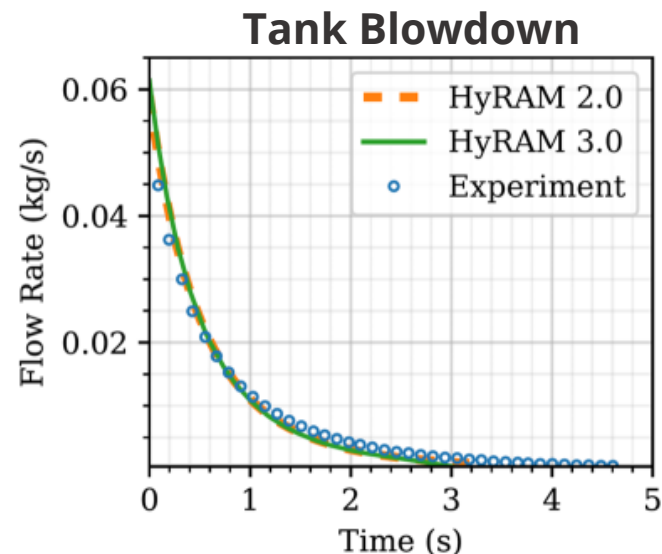
- Tank blowdown
- Unignited dispersion jet plume
- Ignited jet flame
- Accumulation and overpressure inside an enclosure

Both HyRAM 2 and 3 gives reasonably accurate predictions at pressures up to 900 bar

Overall, **HyRAM 3 provides incremental improvement to the accuracy** relative to HyRAM 2

- Reduces conservatism in hazard/risk calculations using HyRAM

Comparison to multiple experimental sources demonstrates accuracy of HyRAM release models over wide range of conditions



Full report published soon at <https://hyram.sandia.gov>



Progress: Liquid Hydrogen Separation Distances

Liquid natural gas (LNG) leak frequencies estimated for DOT PHMSA project

- This cryogenic flammable gas can be used as proxy to give **“informed” basis** for LH2 leak frequencies
- **LH2-specific leak data** from industry partners can “update” leak frequencies for LH2

Leak frequency for 5 different leak sizes distributed as log-normal random variables

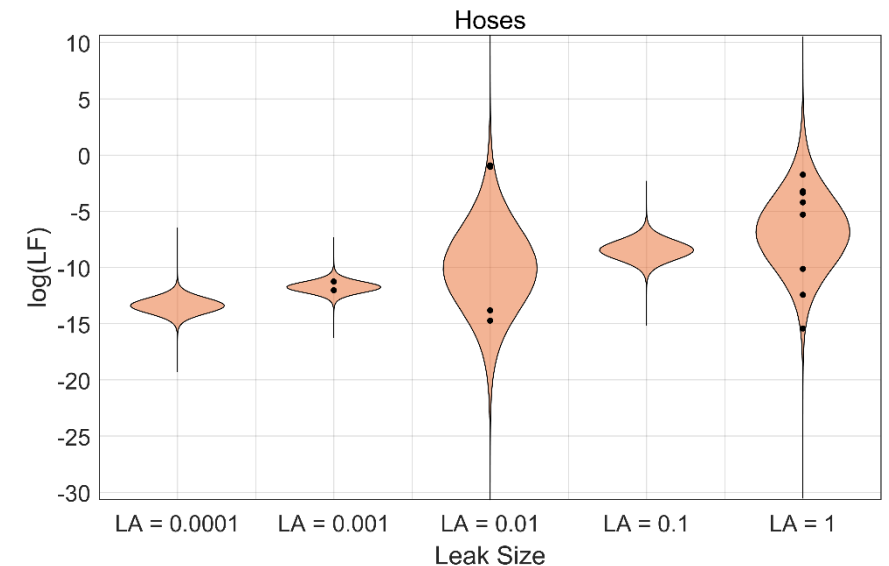
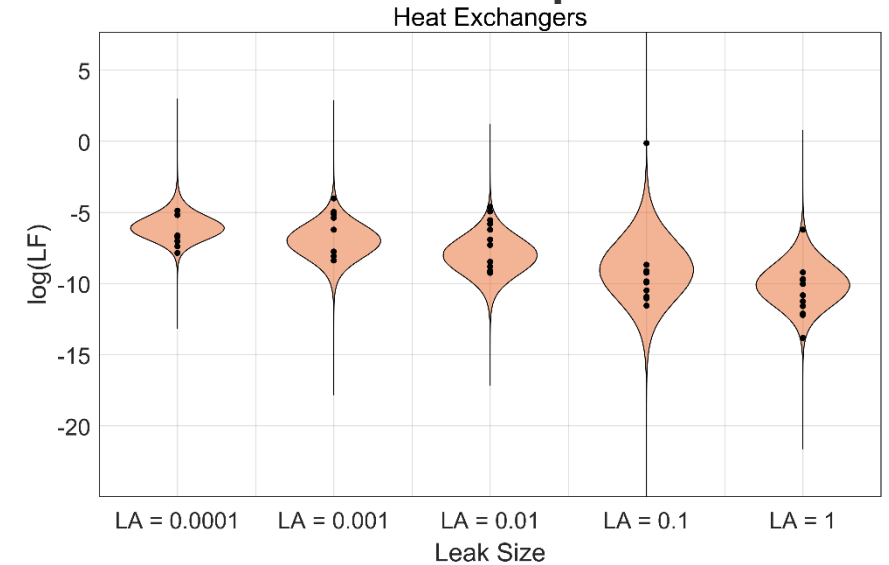
- **Mean or median** can be used for **QRA calculations**
- Probability distribution reflects **lack of data** and **variability within data**

Partial LH2 data obtained from multiple industry partners

- Confirming leak sizes and component “population”

Liquid hydrogen leak frequencies by end of FY, can help inform basis for LH2 setback distances

LNG Leak Frequencies





Progress: Unconfined Overpressure Models for HyRAM

HyRAM currently has **jet flame** model for **immediate ignition** of leak

- Thermal hazard

Overpressure hazard can result if unignited plume **ignites after delay**

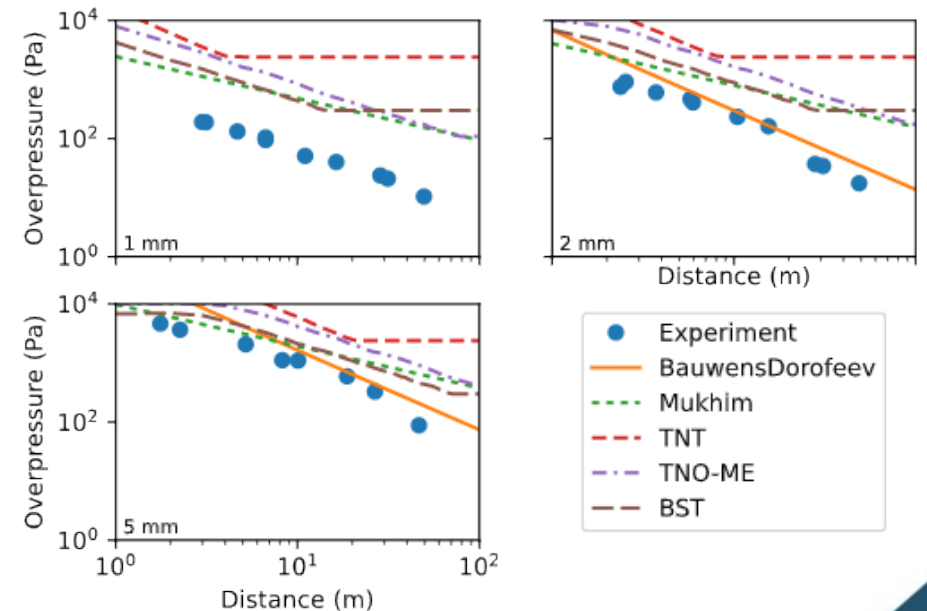
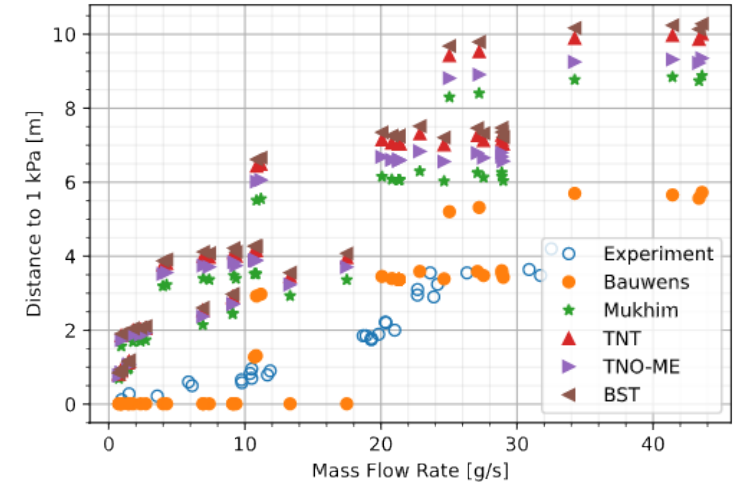
- No confinement
- Different than pressure vessel burst
- Observed in recent real-world events

Multiple models compared to literature data

- TNT Equivalence*
- TNO Multi-Energy
- Baker-Strehlow-Tang*
- Mukhim et al.
- Bauwens and Dorofeev*

* Selected 3 of 5 for incorporation into HyRAM

Unconfined overpressure model will allow for more complete assessment of hydrogen release scenarios





Progress: Codes and Standards Gap Identification for Rail

Reviewing hydrogen-specific standards for rail applicability (e.g., NFPA 2)

- Passenger and freight rail
- Gaseous and liquid hydrogen
- Refueling and maintenance facilities

Related project through DOT FRA reviewing rail-specific standards for hydrogen applicability

- Locomotive
- Tender car
- Tank car

Refueling requirements generally developed for light-duty vehicles

- Bulk liquid hydrogen setback distances on given for up to ~20,000 kg
- Fueling pad for on-road vehicle

Identifying rail-specific SCS gaps to enable future rail applications



Progress: Literature Review of Hydrogen/Natural Gas Blend Releases

Hydrogen blending into natural gas pipelines of interest for H2@Scale

Natural gas (methane) being added to upcoming release of HyRAM

- Pure methane or pure hydrogen; not a mixture

Some property methods exist for modeling mixture

- Pure hydrogen typically more buoyant than pure methane
- Would unconfined release separate?

Literature review to identify data for future model validation

- Experimental data and high-fidelity modeling
- Unignited release from pipeline
- Ignited jet fires
- Accumulation in enclosures

Knowing what has already been published for blends can expedite RCS improvements and risk analysis for this high-interest application



Accomplishment: Hydrogen Regulatory Map

H2@Scale expanding into new sectors

- Transportation – vehicles, rail, maritime, aviation
- Production – distributed, SMR/renewable, offshore
- Storage – electrical grid storage, import/export
- Distribution – pipelines, transportation modes
- Use – heating, electricity, chemicals, transportation

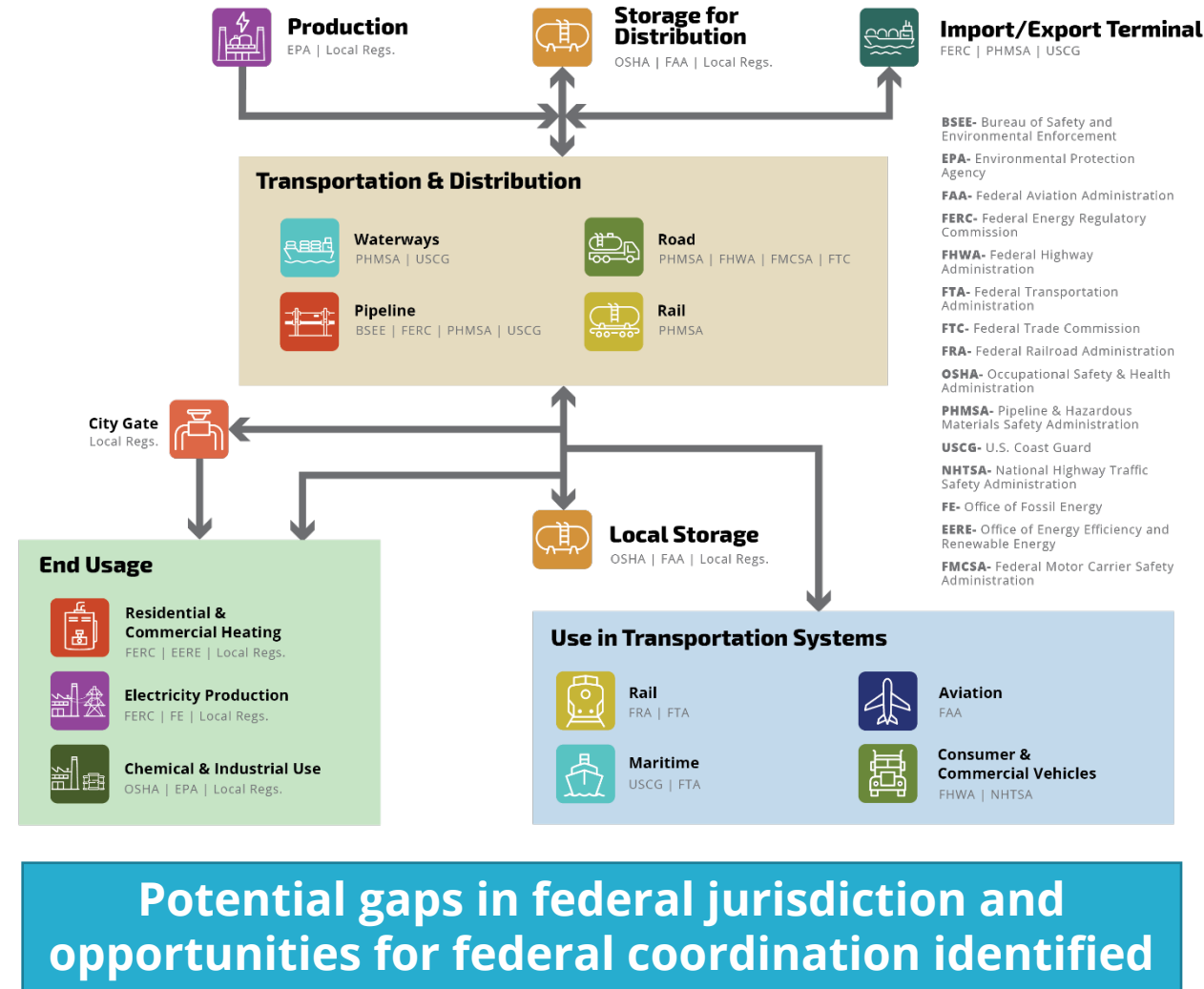
Regulated by federal, state, and local entities

- Current focus on federal oversight for future engagement

Large-scale natural gas infrastructure already exists in federal regs

- Not always specific to hydrogen

Full Report: [SAND2021-2955](https://www.energy.gov/sand/2021-09-29-sand2021-2955)





Response to Reviewer Comments (from 2019)

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 Storage Task Group to provide risk-informed analysis in time for the current code cycle, specifically for liquid hydrogen system leak frequencies and the new release of HyRAM to handle cryogenic plumes

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 User Guide ([SAND2019-8940](#)) describes example calculations, and the updated Technical Reference Manual ([SAND2020-10600](#)) describes model inputs and default value selection in much greater detail than before. 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 physical conditions (temperature and pressure) will have a much wider range of validity than before
- Additionally, the re-validation effort gives the specific comparison data and how well the model matches it
- While some warnings have been improved in the HyRAM software (such as for leak frequencies and valid inputs), there is no “bright line” as to where the accumulation model is or is not valid, and so identifying a specific value at which the input is no longer valid is problematic



Collaboration and Coordination

Relationship	Category	Collaborator	Role
CRADA Partner	Industry	FirstElement Fuel	In-kind support, data exchange for QRA tool
CRADA Partner	Industry	Frontier Energy, (Manager of the California Fuel Cell Partnership)	Develop industry stakeholders in support of LH2 behavior characterization
CRADA Partner	Industry	Air Liquide	LH2 release behavior and risk assessment comparison
Code Committee Members	Codes and Standards Organizations	NFPA 2, 55	Task group support for separation distances, vent pipes, balloons
Collaborator	National Lab	Pacific Northwest National Laboratory	Hydrogen tools portal, Hydrogen Safety Panel, Center for Hydrogen Safety
Collaborator	National Lab	National Renewable Energy Laboratory	Technical exchanges on QRA, safety codes and standards committees and task groups
Collaborator	National Lab	Argonne National Laboratory	Design specifications for rail based on locomotive design and costing analysis
Stakeholder	Government Agency	Caltrans	Feedback on designs and operating assumptions for rail applications
Stakeholder	Municipality	San Bernardino County Transit Authority	
Stakeholder	Industry	DB Engineering & Consulting	



Remaining Challenges and Barriers

Science-Based Code Improvements

- Need more complete data for liquid hydrogen system component failures and leaks
- Liquid hydrogen pooling difficult to model without expensive CFD; even then, little validation data
- Code requirements depend on ignition probabilities in risk assessments
- Few science-based requirements for hydrogen/natural gas blends

Hydrogen in Other Applications

- Vehicles, rail, maritime, and aviation all very different modes of transport with very different safety concerns
- Non-transportation storage and use also have different safety considerations
- Larger potential release quantities need specific consideration for supporting infrastructure



Proposed Future Work

Rest of FY21:

- Develop LH2 leak frequencies as defaults in HyRAM and to support LH2 risk assessments based on data from industry partners
- Provide support for sound scientific basis for revised bulk LH2 separation distances in NFPA 2/55 through risk assessment and consequence modeling
- Identify gaps in safety, codes, and standards for hydrogen rail applications
- Identify literature data hydrogen/natural gas blend releases
- Incorporate unconfined overpressure model into HyRAM+ and release publicly

Proposed Work in FY22:

- Estimate better values (with uncertainty) for ignition probabilities in risk assessments
- Identify and assess model of hydrogen/natural gas blends for inclusion in HyRAM+
- Identify and assess model for liquid hydrogen pooling for inclusion in HyRAM+
- Assess releases in enclosed spaces (e.g., maintenance facilities, tunnels) for heavy-duty transportation and other applications to identify prevention/mitigation strategies

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



Summary

Goal: Provide science & engineering basis for assessing safety (risk) of H2 systems and facilitate use of that information in SCS and permitting

Relevance: Reducing barriers related to limited availability and access to safety data and assessments for SCS revision

Approach: Coordinated activities ensures accelerated transfer of R&D results into codes and standards and R&D focused on high-impact stakeholder problems

Accomplishments:

- Released HyRAM 3.0 with cryogenic release capabilities
- Published hydrogen regulatory map for federal oversight
- Re-validation study with additional data sources for HyRAM 3

Progress:

- Leak frequencies of LH2 estimated using industry data and LNG prior
- Gap identification for rail and literature search for H2/NG blend releases underway
- Unconfined overpressure model identified for inclusion in future HyRAM release



Technical
Backup and
Additional
Information

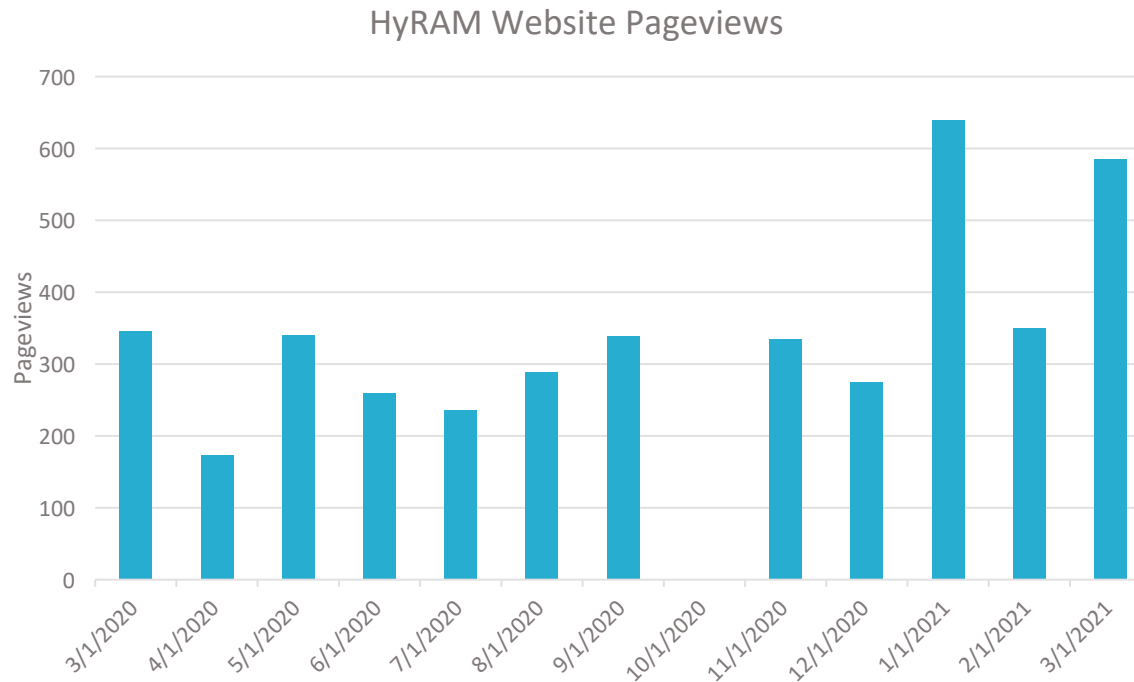


Technology Transfer Activities

Hydrogen Risk Assessment Models (HyRAM) Copyright SCR #1703, Open Source under GNU General Public License (GPL) v3.0

Total downloads of HyRAM software since version 2.0 (open-source release): 2,479

- **Most recent version** (version 3.0.1) has **600 downloads** as of March 2021



** Website transition during October 2020 made pageview statistics unreliable*



Progress Toward DOE Targets or Milestones

2015 SCS MYRDD: “Most SCS activities do not have quantifiable technical targets”

SCS Program Records 15006 and 19005 both relate to NFPA 2 separation distances

- Simple reductions in separation distances are not beneficial if safety is reduced

2015 SCS MYRDD Goal:

- “Develop and implement practices and procedures for the safe conduct of DOE-funded hydrogen and fuel cell projects. Provide the scientific and technical basis for requirements in critical RCS to enable full deployment of hydrogen and fuel cell technologies in all market sectors.”

2015 SCS MYRDD Objective	Project Progress
Support and facilitate development and promulgation of essential codes and standards to enable widespread deployment and market entry of hydrogen and fuel cell technologies and completion of all essential domestic and international RCS by 2020.	Hydrogen regulatory map published
Conduct R&D to provide critical data and information needed to define requirements in developing codes and standards.	Identified unconfined overpressure model to better inform separation distances outdoors Obtained partial data on liquid hydrogen leak frequencies from industry partners to better inform future risk assessments and justification for hazard scenarios
Develop and enable widespread sharing of safety-related information resources and lessons learned with first responders, authorities having jurisdiction (AHJs), and other key stakeholders.	Released HyRAM 3.0 with abilities to model cryogenic plumes for small liquid hydrogen releases



Special Recognitions and Awards

Chris LaFleur was awarded the 2020 Hydrogen and Fuel Cells Program Special Recognition Awards for Safety, Codes, and Standards



Publications and Presentations

Publications

- C.B. LaFleur, A.M. Glover, A.R. Baird, C.J. Jordan, B.D. Ehrhart “Alternative Fuel Vehicles in Tunnels” Sandia National Laboratories Report SAND2020-5466, May 2020
- B.D. Ehrhart and E.S. Hecht “Hydrogen Risk Assessment Models (HyRAM) Version 3.0 Technical Reference Manual” Sandia National Laboratories Report SAND2020-10600, September 2020
- B.D. Ehrhart, S.R. Harris, M.L. Blaylock, A.B. Muna, S. Quong “Risk assessment and ventilation modeling for hydrogen releases in vehicle repair garages” International Journal of Hydrogen Energy 46(23), p. 12429-12438, March 2021
- A.R. Baird, B.D. Ehrhart, A.M. Glover, C.B. LaFleur “Federal Oversight of Hydrogen Systems” Sandia National Laboratories Report SAND2021-2955, March 2021

Presentations

- E.S. Hecht and B.D. Ehrhart “HyRAM simulations of LH2 hazard distances” Presented to NFPA 2 Storage Task Group, June 2020. SAND2020-6054 PE
- B.D. Ehrhart “Quantitative Risk Assessment Updates: Repair Garage Ventilation and Liquid Hydrogen Leak Frequencies” Presentation to Codes and Standards Tech Team (CSTT), July 9, 2020. SAND2020-6914 PE
- B.D. Ehrhart “Sandia Work on Hydrogen for Transportation Systems” Presentation to East Bay Municipal Utility District (EBMUD), August 20, 2020. SAND2020-8750 PE
- B. Ehrhart “Background and Current Work on Hydrogen for Rail” Monthly Zero Emission Transport (ZEHTRANS) Meetings, August 21, 2020. SAND2020-8731 PE
- B. Ehrhart “Hydrogen Leak Frequency Distribution Estimation” CHS H2 Equipment & Component Failure Rates Working Group Meeting, January 29, 2021. SAND2021-0758 PE
- B. Ehrhart “Past Examples and Current Efforts in Hydrogen for Rail” California Fuel Cell Partnership Working Group Meeting, March 17, 2021. SAND2021-2874 PE
- B. Ehrhart “HyRAM Risk Calculation Overview” SafeTec Workshop, March 16, 2021. SAND2021-2956 PE