Enabling Hydrogen Infrastructure Through Science-based Codes and Standards

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Project ID SCS025 -

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Overview

Timeline

- Project start date: Oct. 2003
- Project end date: Sept. 2017*

*Project continuation and direction determined annually by DOE

Barriers

F. Insufficient technical data to revise standards
H. Insufficient Synchronization of National Codes and Standards
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

- FY16 DOE Funding: $230K
- Planned FY17 DOE Funding: $475K

Partners

Industry & research collaborators:
Linde, Air Products and Chemicals Inc., HySafe

SDO/CDO participation:

NFPA2, ISO TC197, DOT Tunnel Jurisdictions

International engagement:
HySafe, HyIndoor, IEA HIA Task 31

Relevance

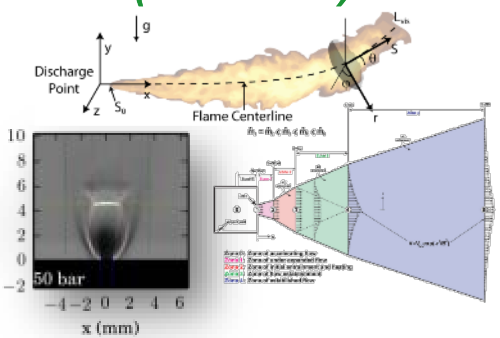
Objective: Utilize fundamental science and engineering to enable the growth of hydrogen infrastructure and improve the basis of Codes & Standards

- Revise/update codes & standards that address critical limitations to station implementation
- Streamline cost and time for station permitting by demonstration of alternative approaches to code compliance

Barrier from 2013 SCS MYRDD	SNL Impact
F. Insufficient technical data to revise standards	Build tools to enable industry-led C&S revision and safety analyses to be based on a strong science & engineering basis
H. Insufficient Synchronization of National Codes and Standards	Develop and demonstrate risk-equivalent station design
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

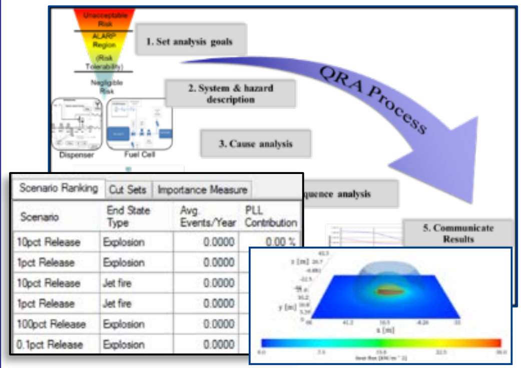
Behavior R&D (SCS 010)



Develop and validate scientific models

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

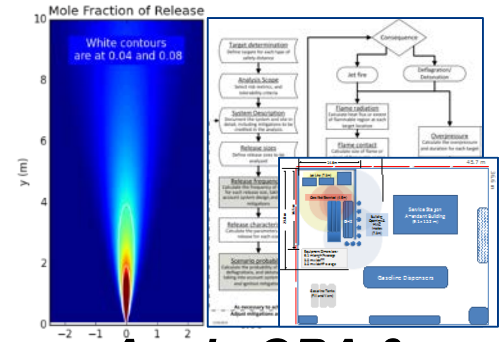
Risk R&D (SCS 011)



Develop integrated methods and algorithms

for enabling consistent, traceable and rigorous QRA

Application in SCS (SCS025)



Apply QRA & behavior models to real problems

in hydrogen infrastructure and emerging technology

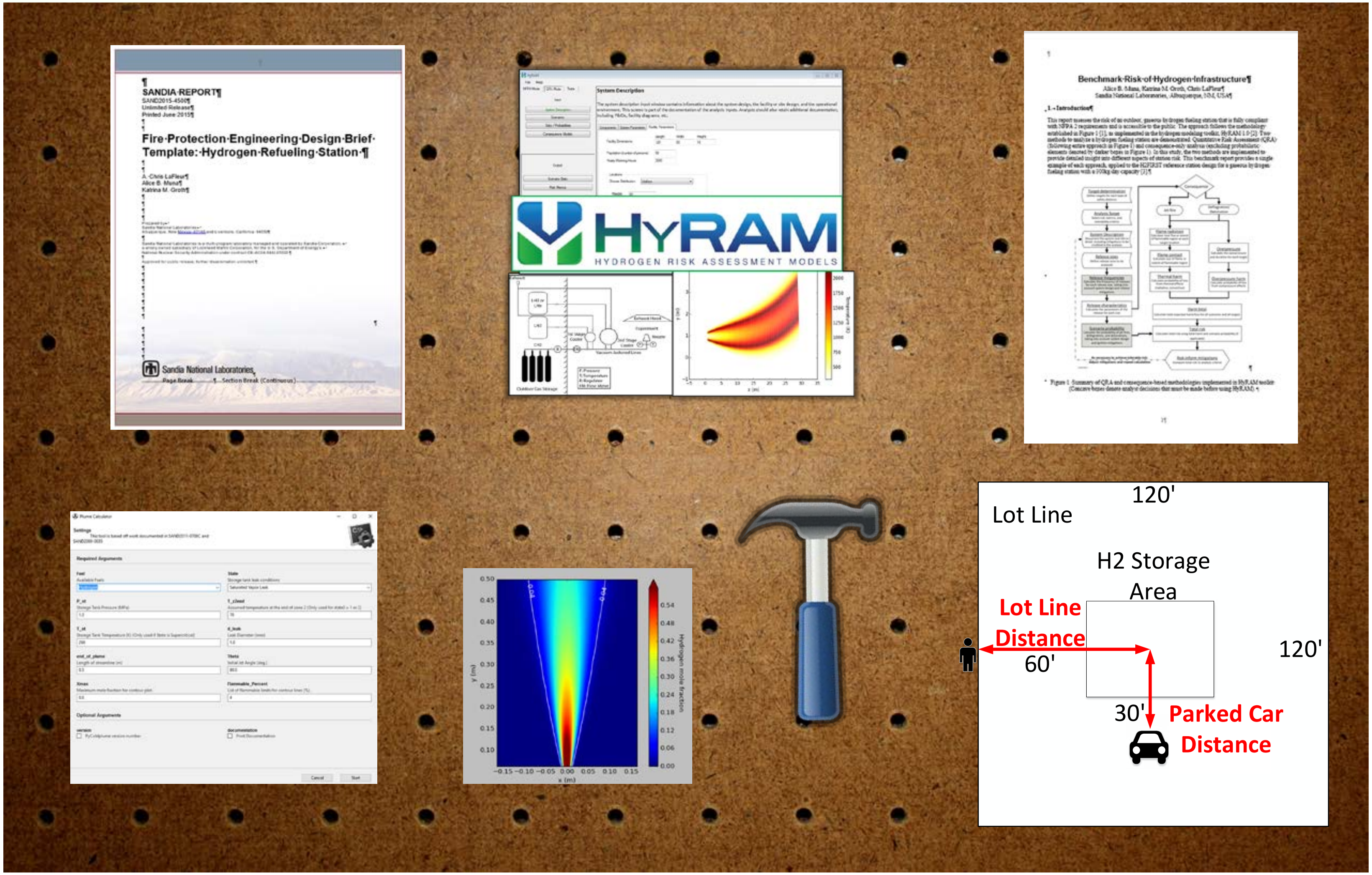
Developing methods, data, tools for H_2 safety & SCS

Approach / FY16-17 Milestones

Impact Areas	Completion date or status
Science-based Hydrogen Storage Code Improvements	
• **Update Science Basis of Liquid Separation Distances in NFPA 2/55**	
• Analyze Scenarios for Basis of Code Revision Using Near Field Model • Characterize Scenarios with Large Scale Release Experiment Results and Models • Develop Risk-Informed Separation Distance Revision Proposals to Code	June 2017 December 2017 2018/2019
• **Update Gaseous Separation Distances Based on Revised Risk Criteria**	
• Distances Approved by Technical Committee • Address Public Comments, Recalculate for Second Draft of NFPA 2	January 2017 December 2017
• **Synchronize with International Standards**	
• ISO TC 197 Working Group – CD2 Review	April 2017
Evaluation of Existing Tunnel for FCEV Safety	
• Comprehension of Massachusetts Specific Safety Concerns • Initial Calculations of FCEV compared to traditional Vehicle Fire HRR • Develop detail Heat Transfer and CFD models of Tunnel Fire	October 2016 January 2017 Ongoing (80%)
Demonstrate Performance-based Design for a Real-world station	
• Station selection – • Develop PBD design, justification and station permitting	Several Considered Pending Station Selection

Approach: Enabling Hydrogen Infrastructure

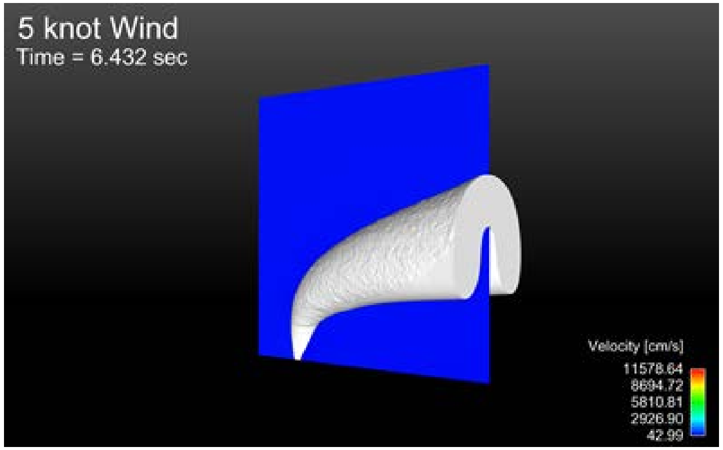
Tools Developed:



Progress: Science-Based Prescriptive Requirement Revisions Bulk Liquefied Hydrogen

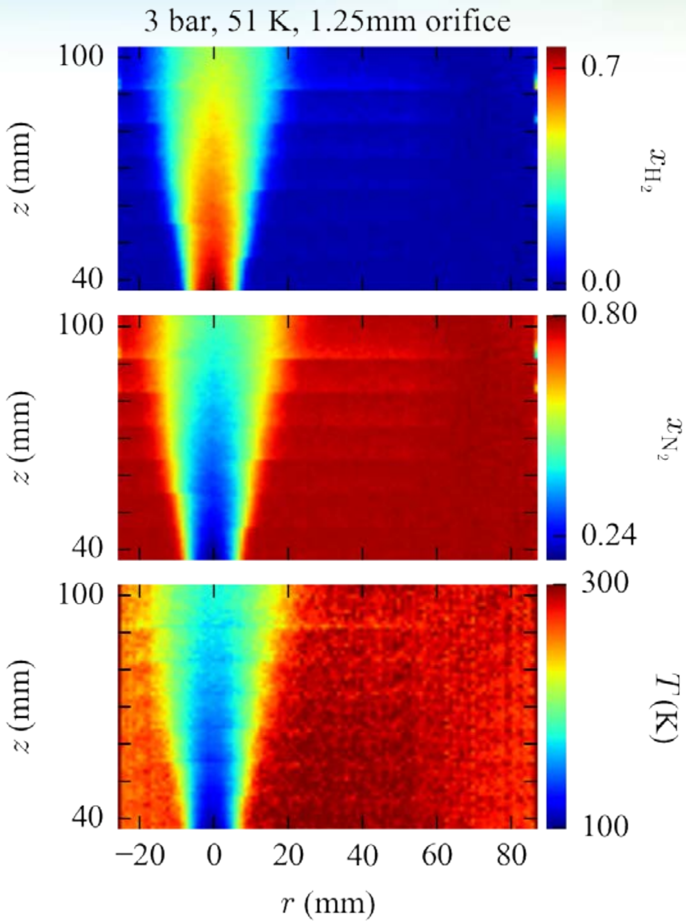
- Goal: Use QRA tools and methods to revise bulk liquid hydrogen system separation distances in NFPA 55/NFPA 2
- Progress:
  - LH2 release modeling validation work briefed to storage task group
  - Modeling of vent cap exit orientation shows vertical release has much smaller horizontal extent of flammable concentration
  - Nine scenarios of concern will be addressed through research and development of LH2 release characterization models

Characterization of the release scenarios will allow the setback distances to be revised based on the physics models



Progress: LH2 Informing Science-based Code Revisions

- Goal: Use QRA tools and methods to revise bulk liquid hydrogen system separation distances in NFPA 55/NFPA 2
- Progress:
  - Using planar Raman imaging to measure concentration of cryogenic releases of 2 and 4 bar hydrogen at 64K
  - Validating testing is ongoing
  - Multi-Party CRADA with Bki and Fire Protection Research Foundation has allowed industry to provide matching funds in support of LH2 model validation experimentation efforts
  - Details given in SCS-010 AMR presentation



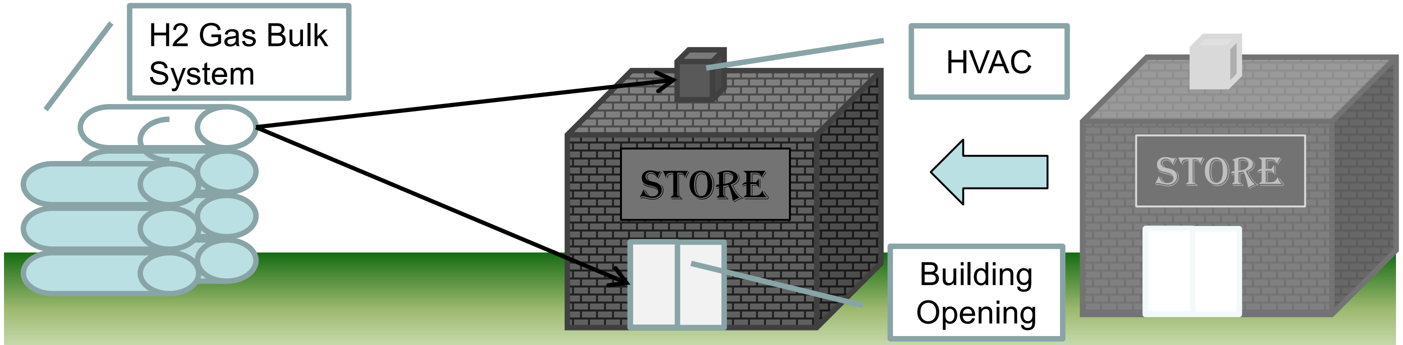
Validated LH2 release model will be used to risk-inform the revised LH2 bulk separation

Progress: Science-Based Gaseous Separation Distances

- Goal: Update NFPA 55/2 gaseous separation distances using scientific justification for risk criteria
- Progress:
  - Gaseous revision table was accepted by TC 55/2 for the first draft meeting
  - Public comment period and second draft meeting still remain

Exposures	Code Version	Separation Distance			
		>0.10 to 1.72 MPa	>1.72 to 20.68 MPa	>20.68 to 51.71 MPa	>51.71 to 103.43 MPa
Group 1 Exposures	2016	12 m	14 m	9 m	10 m
	2019	**5 m**	**6 m**	**4 m**	**5 m**
Group 2 Exposures	2016	6 m	7 m	4 m	5 m
	2019	**5 m**	**6 m**	**3 m**	**4 m**
Group 3 Exposures	2016	5 m	6 m	4 m	4 m
	2019	**4 m**	**5 m**	**3 m**	**4 m**

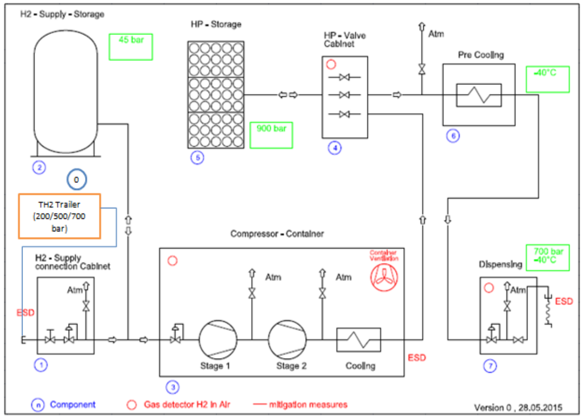
2016: 10 m for 70 MPa storage
2019: 5 m for 70 MPa storage

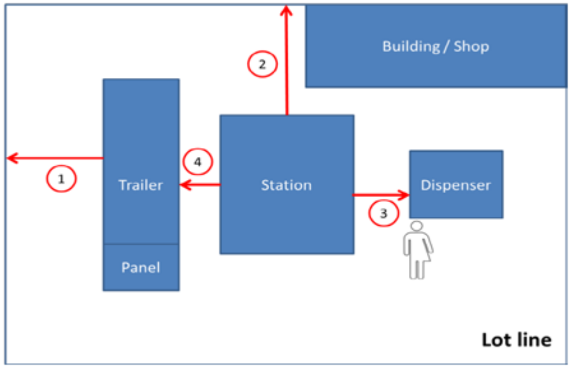


Risk-informed code requirements based on risk threshold revisions enable more sites to readily accept hydrogen infrastructure

Progress: International agreement on approach to safety distances in ISO CD-19880-1 Annex A

- ISO CD-19880-1 Annex A Drafted
  - Sub-team agreed to the approach: US, UK, Japan, Germany, France
  - Developed 3 case studies each with 5 example calculations utilizing HyRAM tool
- Impact:
  - Reducing cross-border challenges
  - EIGA likely to adopt approach using HyRAM tool
- HyRAM directly enabled progress:
  - Real-time use of HyRAM enabled consensus
- Status:
  - ISO now at CD 2 stage – voting in April 2017



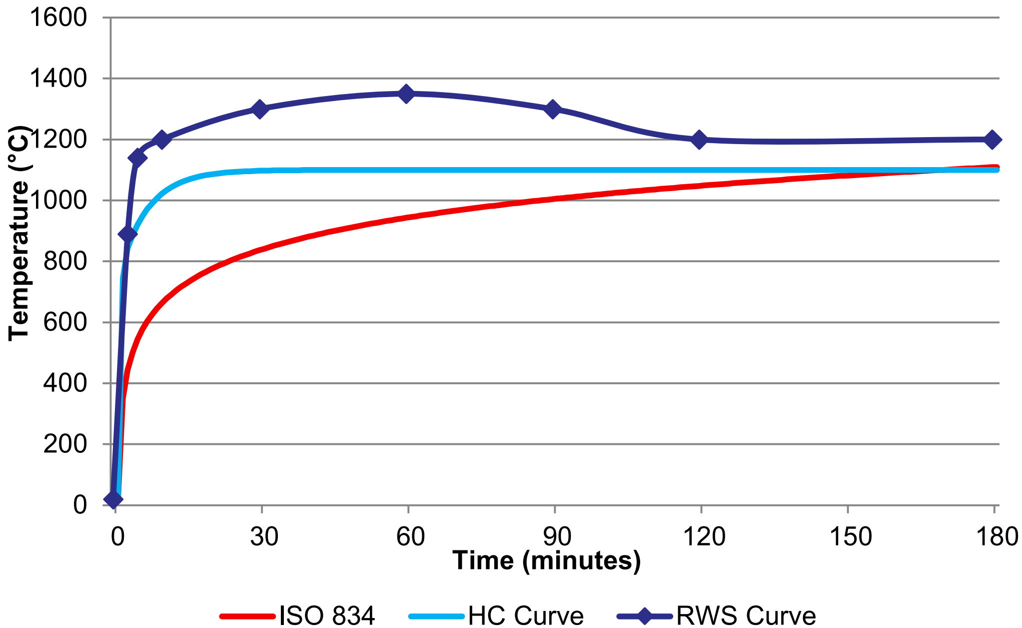


HyRAM enables standardization of safety distance calculations in ISO

Approach: Enable FCEV Access to Northeast Corridor Tunnels

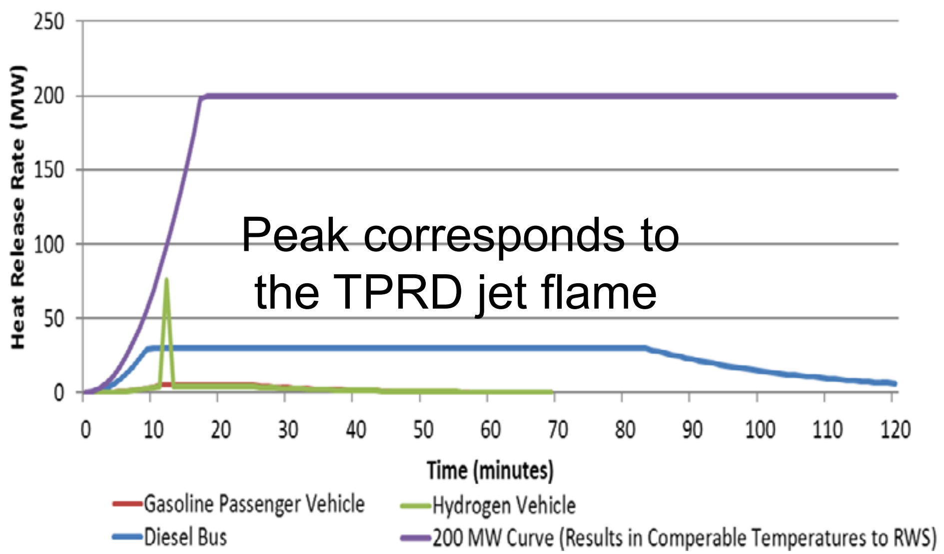
- Goal: Provide scientific modeling and analyses for Northeast corridor AHJs and emergency responders on hydrogen vehicle safety in tunnels
- Approach:
  - Initial analysis to compare anticipated hydrogen release scenario with existing code requirement
  - Coupled Computational Fluid Dynamic (CFD) and Heat Transfer models to evaluate hydrogen fire impact on steel structure

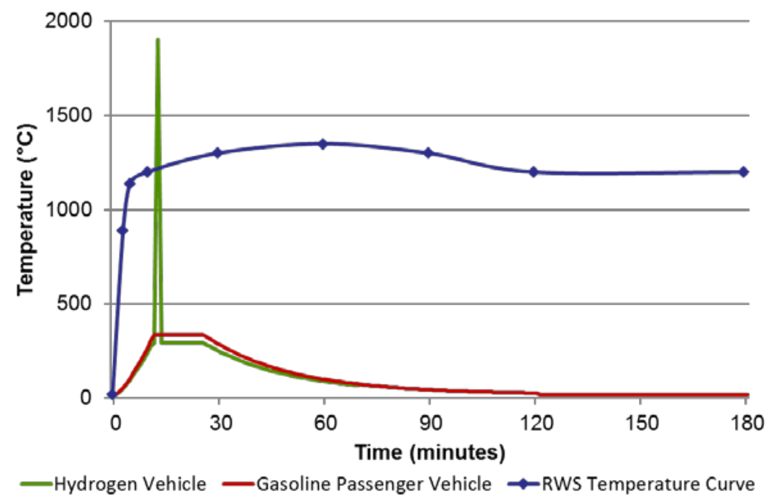
Risk analysis and modeling will provide scientific basis for regulatory determinations for FCEV access



Progress: Tunnel Safety Evaluation

- Progress:
  - Conducted initial meeting with Massachusetts DOT and emergency responders and Maryland AHJ
  - Developed risk analysis framework and identified scenarios of concern
  - Initial analysis of scenario involving accident with hydrocarbon fire, FCEV has flipped and the TPRD is aimed at the ceiling

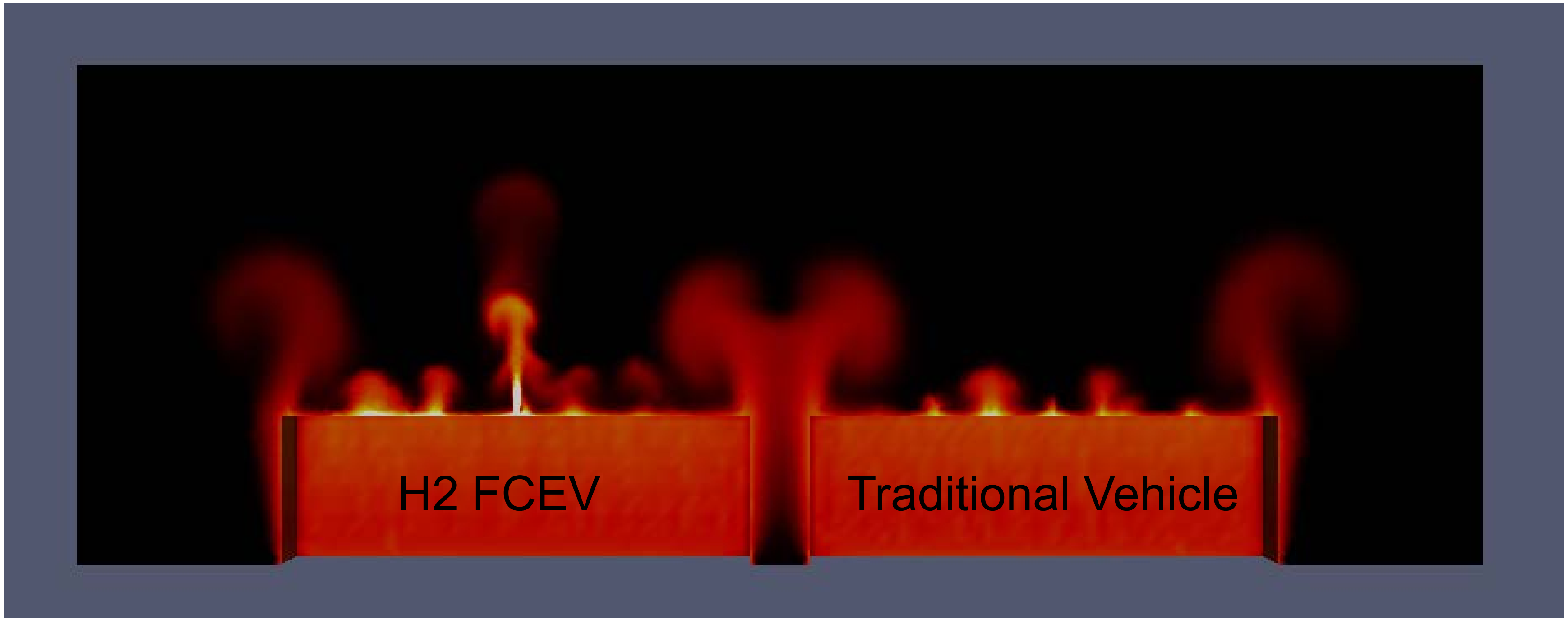




Risk analysis and modeling results will be communicated to AHJs to assist in their decision-making.

Progress: Tunnel Safety Evaluation

- Coupled Computational Fluid Dynamic (CFD) and Heat Transfer models to evaluate hydrogen fire impact on steel structure
- Complex fire model due to combination of hydrocarbon fire and separate hydrogen fire at TPRD outlet
- Once complete, model will evaluate steel strength and potential for explosive spalling of concrete



Progress: Real World Application of Alternate Means

- Goal: Establish alternate means as a viable station permitting option with our industry partner, Linde
- Progress:
  - Developed compliance substantiation for compressor enclosure
  - 2016 NFPA 2 Hydrogen Equipment Enclosure Issues
    - 2 hour 'wall' separation between H2 storage and compressor/electrical area
    - NFPA 68 compliance (meets European standards)
  - Evaluated multiple leak scenarios to demonstrate that the intent of the prescriptive requirements are met and the alternate design incorporates measures to ensure equivalent system safety
- Looking for opportunity to permit an Alternate Means station that challenges separation distances

Demonstrating alternate means of compliance increases options for industry in siting hydrogen fueling stations and overall confidence in the performance-based approach for station design

Response to Previous Year Reviewers' Comments

2016 AMR Reviewer Comment	Response
"The project should work directly with AHJs in the upcoming states of deployment." "Outreach and benchmarking are both weaknesses."	More is being done to outreach to the AHJs, particularly in the work on tunnel safety analysis.
"Instead of just being science-based, it is important that C&S are evidence-based, which would include science, best practices, and lessons learned."	The technical committee uses their expertise in science, best practices and lessons learned in order to make updates to the code.
Doing a real-world, actual, in-the-retail-fueling-environment application of alternate means will be of great value to various interested parties: station developers and authorities having jurisdiction, along with other city entities involved in the permitting process, and even the state of California (from the funders to the governor's office). The application is very valuable.	Agreed. Further discussions are planned to attempt to engage a station sponsor in the real world application of an alternate means station.

Collaborations

Relationship	Partner	FY 15 - FY16 Role
CRADA	**Industry:** Linde Group, Industrial gas supplier	CRADA for In-kind support, data exchange for QRA tool and QRA demonstration activities, real world station for alternate means permitting
CRADA	**Industry**: BKi (Manager of the California Fuel Cell Partnership)	Develop industry stakeholders in support of LH2 Behavior Characterization
CRADA	**Code Industry**: Fire Protection Research Foundation (NFPA)	Lead stakeholder oversight panel and enable link to NFPA code process
Collaborator	**International :** IA HySafe	Technical exchanges, ISO
Collaborator	**Federal Laboratory**: Pacific Northwest National Laboratory	Hydrogen tools portal, Hydrogen Safety Panel, hydrogen mitigations forum
Collaborator	**Federal Laboratory**: National Renewable Energy Laboratory	Safety code and standard committee leadership, hydrogen mitigations forum

SDO/CDO memberships
NFPA 2 ICC
ISO TC 197 WG24
CGA
CSA HGV4.9

Organization memberships*
HySafe
IEA HIA Task 31 H2USA Locations WG H2USA Stations WG
DOE CSTT

Technical exchanges, presentations & discussions
CaFCP, ASME
DOE Hydrogen Safety Panel, DOT FRA
PNNL, NREL
AIST (Japan), HyIndoor (EU)

Remaining Challenges and Barriers

- Science-based Code Improvements
  - Validation of the cold plume release model does not characterize liquid release scenarios needed for code committee revisions to bulk liquid hydrogen separation distance table
  - Liquefied hydrogen system leak size and frequency data is not available to allow the QRA to inform the code committee
  - Consensus agreement on suitable means of quantifying hydrogen system mitigation features is not reached
- Hydrogen Tunnel Safety
  - Local AHJ acceptance may be on a case-by-case basis since each tunnel is unique

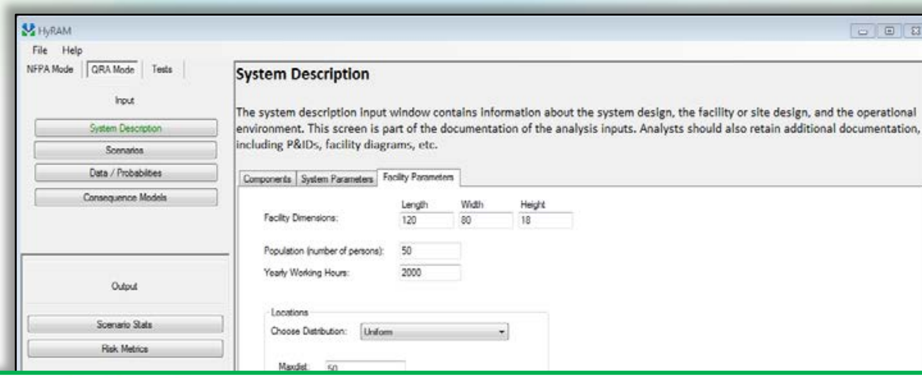
Proposed Future Work

- Remainder of FY17
  - Analyze LH2 scenarios with cold plume model evaluate revisions to separation distances
  - Complete coupled CFD and heat transfer modeling scenarios to support hydrogen vehicle tunnel safety
- FY18
  - 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.
- Out-years
  - Characterize full bulk LH2 release scenarios to support mid-cycle temporary interim agreement (TIA) code revision

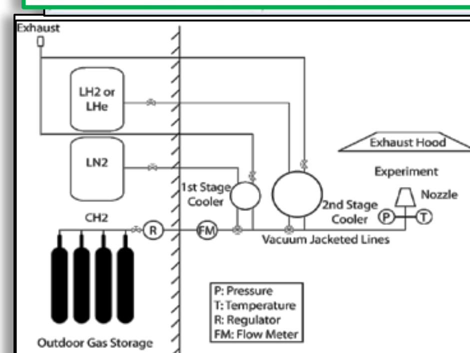
- Any proposed future work is subject to change based on funding levels.

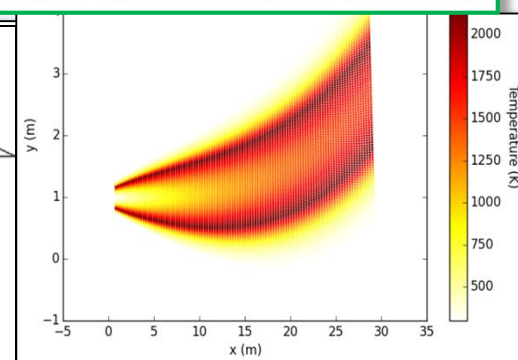
Technology Transfer Activities

- Technology transfer strategies are tied to the accessibility of HyRAM QRA tool kit to other users (AHJs, Station designers, etc.) utilizing alternative means of code compliance
- Refer to AMR SCS-011 presentation



HyRAM
HYDROGEN RISK ASSESSMENT MODELS





Summary

- **Science-based Code Improvements**
  - Addresses: Reducing barriers related to lack of technical data for SCS revision
  - By: Providing expertise to support science-based code revisions of bulk LH2 separation distances
- **ISO TC 197**
  - Addresses: Harmonization with international codes
  - By: Active technical leadership on working groups revising risk-based methodology
- **Northeast Corridor Tunnel Safety Analysis:**
  - Addresses: Usage and Access Restrictions – parking structures, tunnels and other usage areas
  - By: Providing scientific analysis for regulatory determinations of FCEV access
- **Alternate Means of Code Compliance**
  - Addresses: Education of AHJs, Insufficient technical data to revise standards
  - By: Validating and demonstrating alternative methods of code compliance

Technical Back-Up Slides

Details of LH2 Prescriptive Code Revision Scenario Selection and Prioritization

- CGA P-28 *OSHA Process Safety Management and EPA Risk Management Plan Guidance Document for Bulk Liquid Hydrogen Systems* was used as a basis for typical LH2 system definition and HAZOP scenario identification
- Each scenario was reviewed and assigned an Even Hazard and Hazard Severity value.
- Based on these values, the scenario was given a risk ranking which was used to prioritize the scenario

Event Likelihood Classification

Level	Annual Probability	Probability Description
1	Frequent > 1.0	Expected to occur once per year or more frequently.
2	Reasonably probable 1.0 to 0.1	Expected to occur once per 10 years.
3	Occasional 0.01 to 0.1	Expected to occur once per 100 years.
4	Remote 0.001 to 0.01	Expected to occur once per 1000 years.
5	Extremely remote 0.0001 to 0.001	Expected to occur once per 10,000 years.
6	Improbable < 0.0001	Expected to occur less than once per 10,000 years. Extremely unlikely to occur.

Hazard Severity Classification

Level	Description	Potential Consequences
1	Catastrophic	May cause fatality to non-associated members of the public.
2	Critical	May cause severe injury to non-associated members of the public, fatality or serious injury to works of the public, fatality or serious injury to workers of persons conducting business at a refueling site or significant damage to equipment/facilities.
3	Marginal	May cause minor injury, or minor system damage.
4	Negligible	Will not result in injury or system damage.

Risk Ranking:

		Likelihood					
Severity		1	2	3	4	5	6
	1	1	1	1	2	3	4
	2	1	1	2	3	3	4
	3	2	2	3	3	4	4
	4	4	4	4	4	4	4

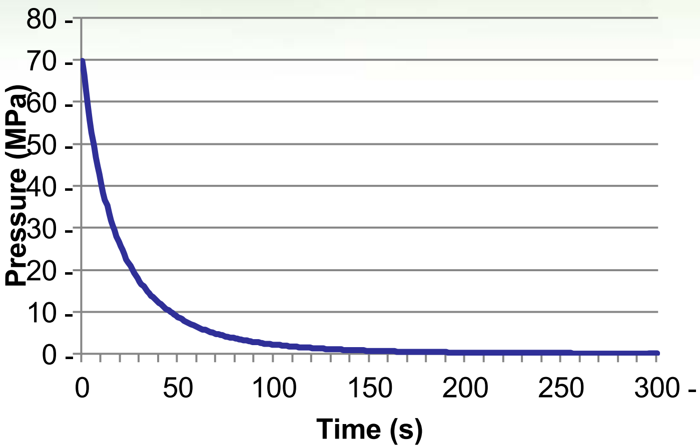
1: High Risk
2: Moderate Risk
3: Low Risk
4: Routine Risk

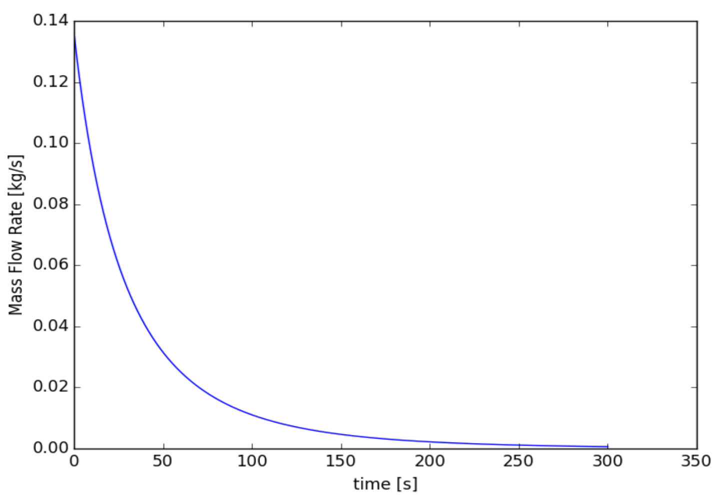
LH2 Prioritized Scenarios to be Used for Separation Distance Revision

	HAZOP Number and Description	
Release scenarios during liquid transfer to bulk storage tank	1.18	High flow of gaseous hydrogen from trailer vent stack due to venting excess pressure after LH2 transfer
	1.19	Normal flow from trailer vent stack due to venting excess pressure after LH2 transfer
	1.6	High flow from line rupture, valve or component failure during transfer process
	1.4	High temperature due to external fire causes high flow venting through tank vent stack
	1.8	Reverse flow during transfer process caused by human error and pressure mismanagement
	1.16	Loss of containment from external impacts, consider all causes

	HAZOP Number and Description	
Release scenarios during normal system operation	4.15	Loss of containment from pipe leading from tank to vaporizer or vaporizer itself caused by thermal cycles or ice falling from vaporizers
	6.15	Misdirected flow caused by operator error resulting in large low level release of cold gaseous hydrogen through bottom drain valve of vent stack during normal tank venting process
	2.1	High pressure because of a leak in inner vessel allowing hydrogen into the vacuum area

Hydrogen Release from a TPRD

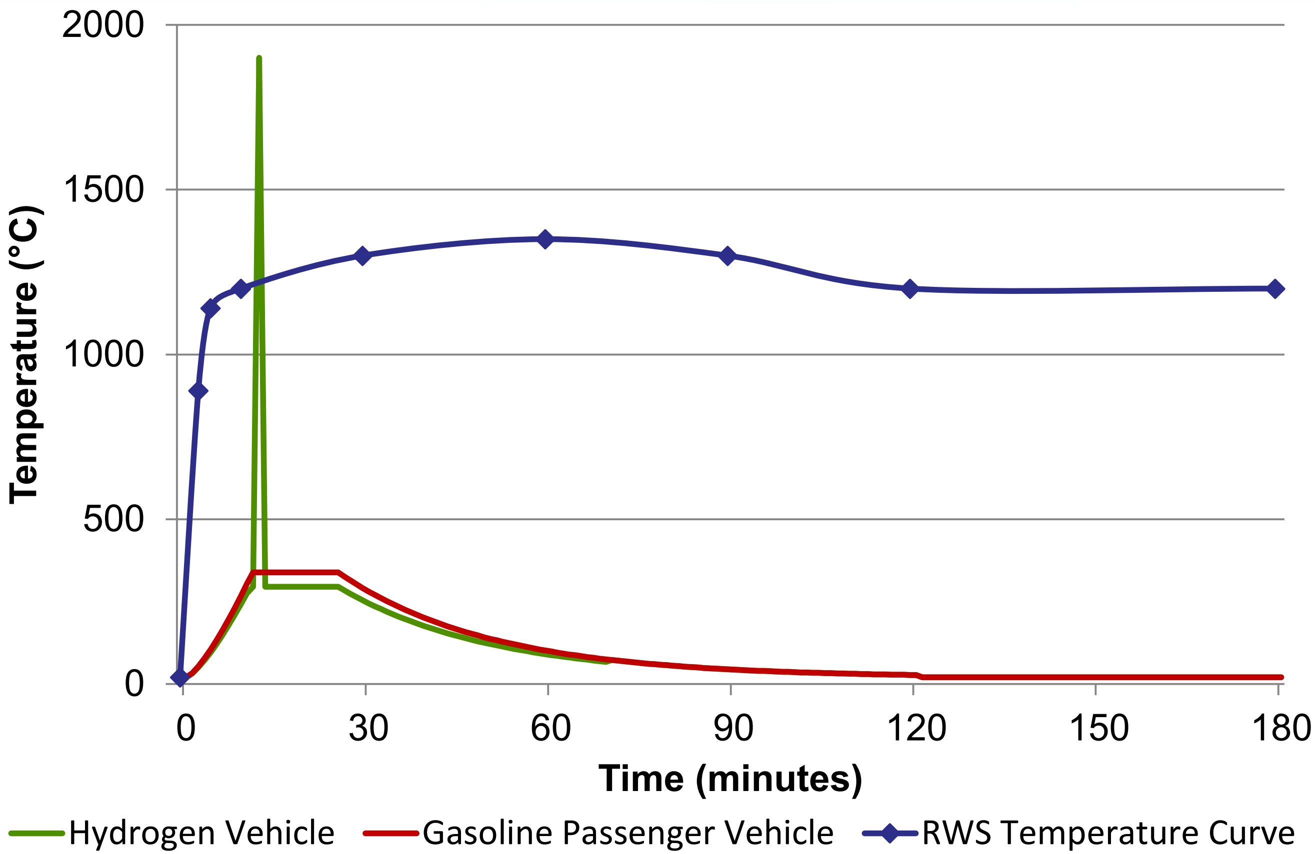




- A hydrogen vehicle is exposed to an external fire causing the TPRD to activate -
- The hydrogen storage tank has the following characteristics: -
  - 125-liters
  - 70MPa
  - TPRD orifice size 2.25 mm -
- Vent time is approximately 300 seconds -
- Most of the hydrogen is released within the first minute

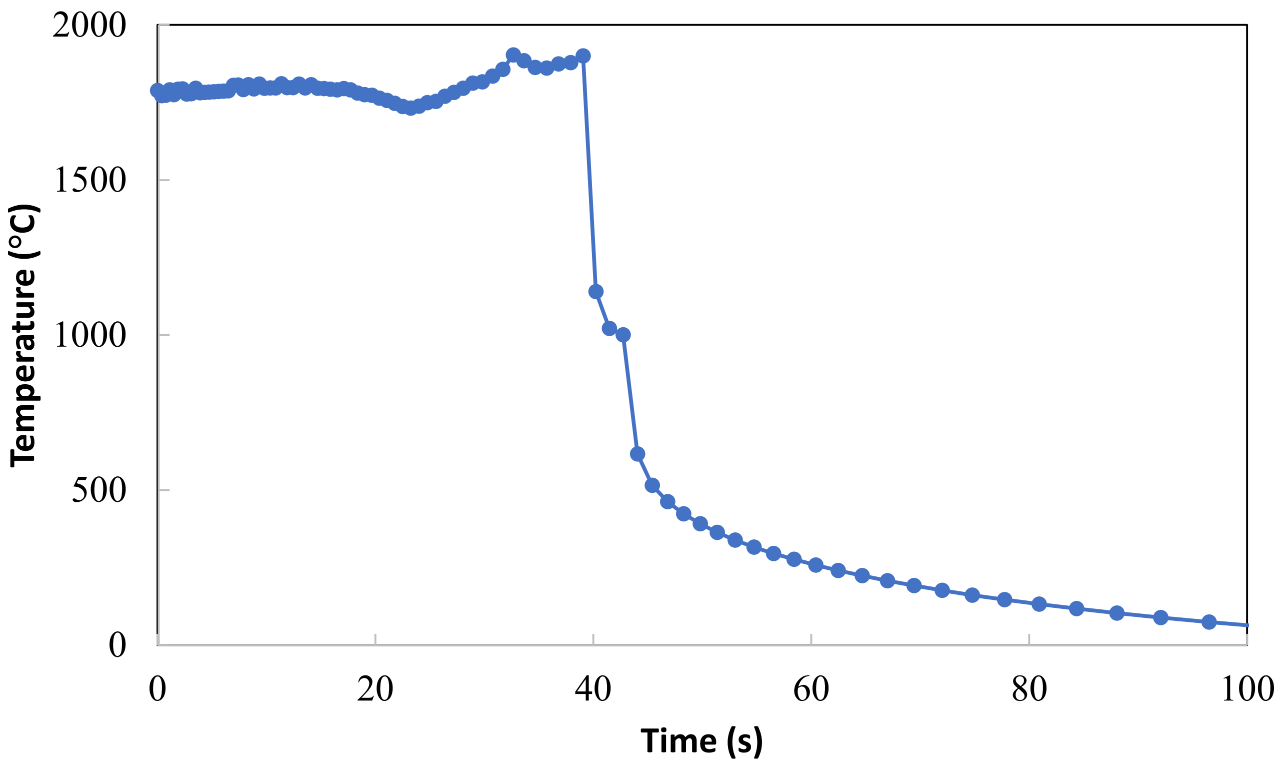
Temperature Calculations

- Spike in temperature is brief (40 seconds)
- Hydrogen radiative heat is low compared to hydrocarbon fires
- Hydrogen-caused temperature spike reduces immediately once flame jet recedes below ceiling height



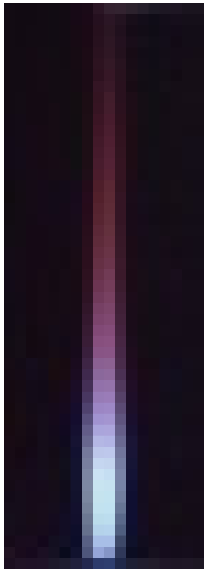
Temperature Calculations at Ceiling for First 100 Seconds

Temperature at 5.2 m



Hydrogen has low flame radiation

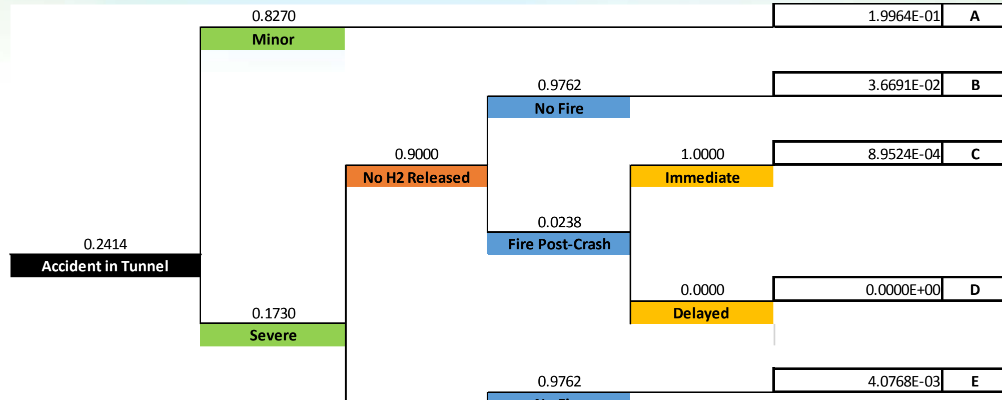
Pure hydrogen and air non-premixed jet flame.

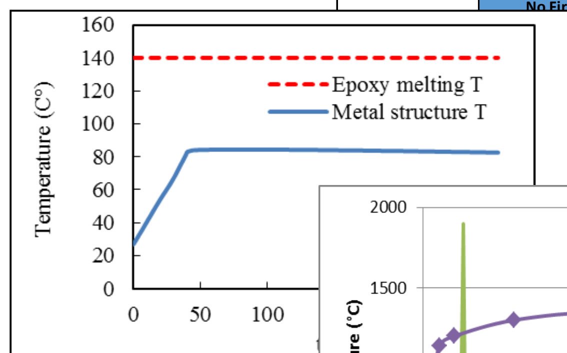


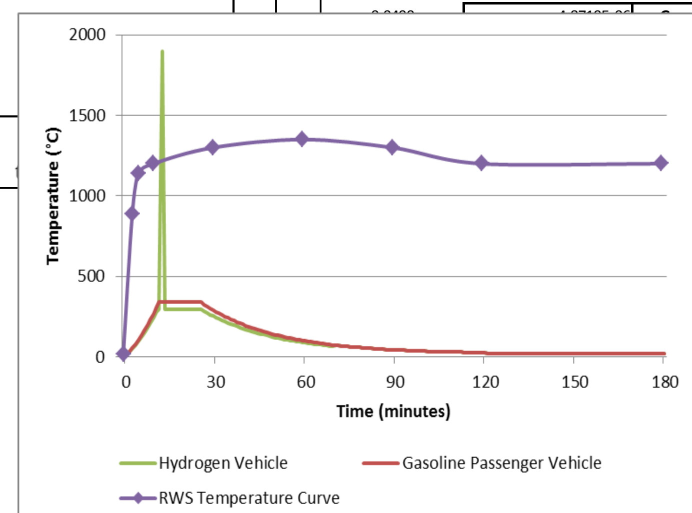
premixed pure hydrogen flame at an equivalence ratio of 0.9

Progress: Technical analysis performed to support hydrogen vehicle tunnel safety

- Goal: Educate east coast corridor AHJs and emergency responders on hydrogen vehicle safety in tunnels
- Progress:
  - Sandia conducted a risk assessment to determine possible scenarios
  - Certain scenarios require further modeling and heat transfer analysis







Risk analysis and modeling results will be communicated to AHJs to assist in their decision-making.