Development, Validation, and Benchmarking of Quantitative Risk Assessment Tools for Hydrogen Refueling Stations

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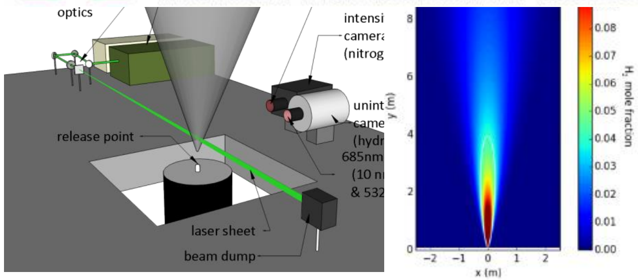
2020 DOE Hydrogen and Fuel Cells Annual Merit Review



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Overview

Timeline

- Project start date: Jan 2019
- Project end date: Dec 2020

Barriers

A. Safety Data and Information: Limited Access and Availability
F. Enabling National and International Markets Requires Consistent RCS
G. Insufficient Technical Data to Revise Standards

Budget

- FY19 DOE Funding: $250k
- FY19 Air Liquide Funding: $250k
- FY19 Air Liquide In-Kind Contribution: $75k
- Total DOE Funds Received to Date: $250k
- FY20 Carryover/planned spending: $360k

Partners

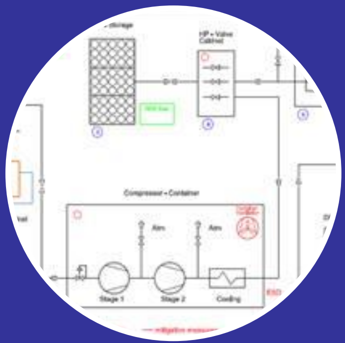
- Air Liquide
- NFPA H2 Storage Task Group
- CGA G-5.5 Testing Task Force

Relevance

Objective: Utilize SNL's hydrogen behavior models and quantitative risk assessment (QRA) methodology to defensibly revise safety codes and standards.

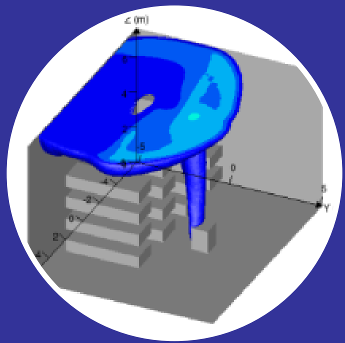
Barrier from 2015 SCS MYRDD	SNL Goal
A. Safety Data and Information: Limited Access and Availability	Build validated H_2 behavior physics models that enable industry-led C&S revision and Quantitative Risk Assessment (QRA).
F. Enabling national and international markets requires consistent RCS	Develop H_2-specific QRA tools & methods which support SCS decisions.
G. Insufficient Technical Data to Revise Standards	Provide tools and validated models to enable better informed codes and standards revisions.

Approach: Benchmark HyRAM software



1. Select station designs to analyze

2. Perform risk analysis of stations using HyRAM while AL performs analysis using their models



3. Analyze and characterize differences between HyRAM and AL internal risk tool (ALDEA) results

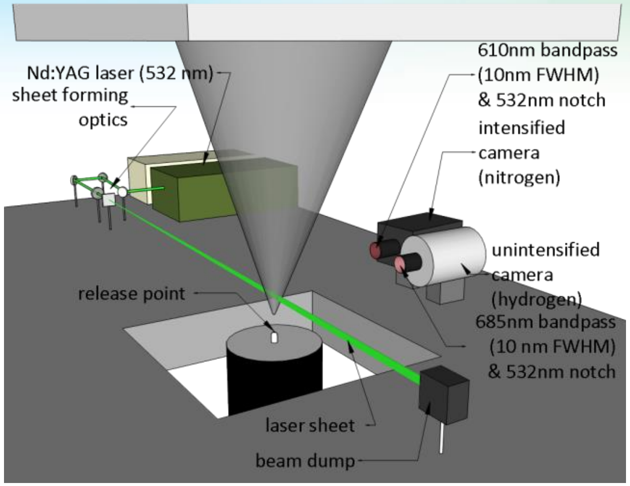
4. Document results

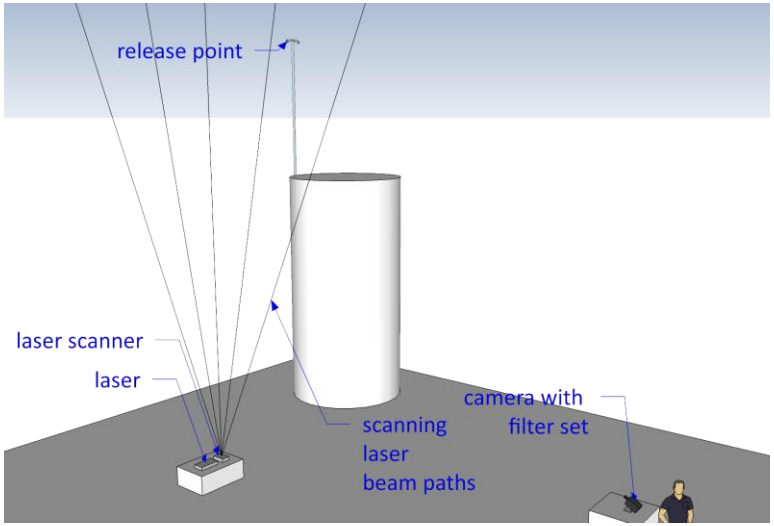
Approach: Make quantitative measurements from large LH_2 experiments that enable defensible codes/QRA

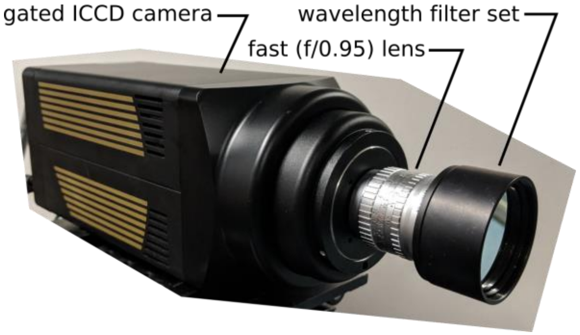
- Support CGA G-5.5 testing task force measurements of LH_2 vent stack flames
  - Hardware support (providing Sandia owned sensors to support the work)
  - Analysis support (Sandia expertise in data analysis and documentation)
- Experimentally measure unignited hydrogen dispersion from LH_2 vent stacks
  - Develop a diagnostic tool for capturing high-fidelity quantitative data for large scale unignited LH_2 experiments
    - non-intrusive (optical diagnostic)
    - Measure concentration in at least 2-dimensions with good temporal resolution
  - Measure vent stack dispersion for a range of flow rates and weather conditions

Approach: Scale-up our lab scale Raman imaging technique

- Use high-speed (low f-number) optics to collect as much light as possible with large field of view to measure entire plume
- High-powered light source required to excite as many molecules as possible
  - High-power laser scanning in space
  - Concentrations measured along a series of lines
- Effective background light suppression is key (both sunlight and illumination source that reflects off of condensed water vapor)
  - Time gating
  - Spectral gating







Accomplishment: Scenarios were identified for comparison of HyRAM to internal Air Liquide models

Comparison of

- Free jets/flames:
  - Low pressure (40 bar)
  - Medium pressure (100 bar)
  - High pressure (700 bar)

→
  - Mass flow rate
  - Distance to 4, 10% concentration
  - Flame length
  - Distance to 3, 5, 8 kW/m^2 heat flux

- Vessels
  - Vessel blowdown
  - Vessel burst
  - Fragments formation
  - Pipeline blast

→
  - Blowdown time as function of leak size
  - HyRAM unable to calculate vessel burst, fragments or blast wave

- Vented explosion
  - Small scale
  - Medium scale

→
  - HyRAM unable to calculate vented explosions

- H_2 build up in a room
  - Closed unventilated
  - Naturally ventilated

→
  - Concentrations over time

- Liquid hydrogen accident scenarios
  - Rupture before pump
  - Rupture after pump

→
  - Preliminary comparisons to ColdPLUME to assist in validation and development

Accomplishment: Good agreement between HyRAM and ALDEA for free jets and flames

Example results for free jet and flame models

	AL results	AL tool	HyRAM results	HyRAM module
Mass release (g/sec)	607	ALDEA-HP	682	Eng. Toolkit
Axial distance at 4% (m)	35	ALDEA-HP	33	Gas Plume Disp.
Axial distance at 10% (m)	14	ALDEA-HP	12.5	Gas Plume Disp.
Flammable mass (4-75%) (kg)	1.2	ALDEA-HP	Not calculated in HyRAM GUI	
Flammable mass (10-75%) (kg)	0.176	ALDEA-HP	Not calculated in HyRAM GUI	
R_{max}(4%)	2	ALDEA-HP	2	Gas Plume Disp.
R_{max}(10%)	0.8	ALDEA-HP	1	Gas Plume Disp.
Distance (200 mbar) (m)	10	ALDEA-ME (5)	Unconfined overpressures not calculated in HyRAM	
Distance (140 mbar) (m)	12	ALDEA-ME (5)		
Distance (50 mbar) (m)	22	ALDEA-ME (5)		
L(flame) (m)	15	ALDEA-Rad	15	Jet Flame
Distance (3 kW/m^2)	10	ALDEA-Rad	10.6	Jet Flame
Distance (5 kW/m^2)	8	ALDEA-Rad	7.2	Jet Flame
Distance (8 kW/m^2)	6	ALDEA-Rad	4.9	12 mm / 100 bar

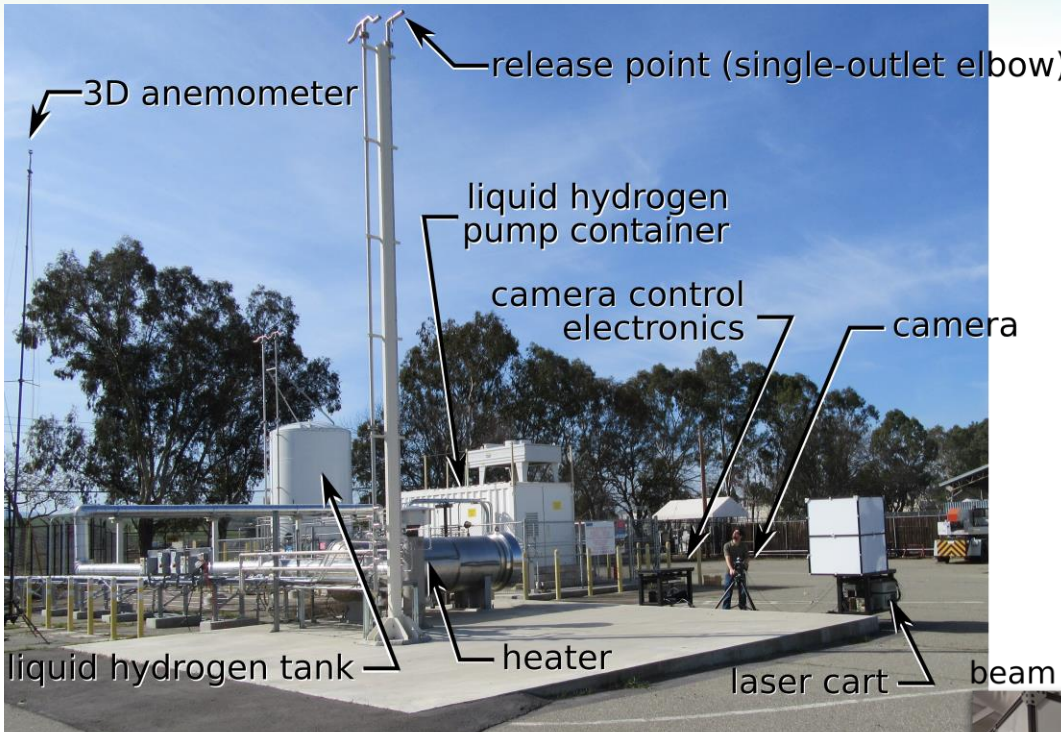
Progress: Final report has been drafted; final analysis of differences and best approach underway

- Report references literature description and validation of models
- Preliminary results:
  - Consequences from free jets and flames are similarly predicted HyRAM and ALDEA
  - HyRAM predicts longer blowdown time than ALDEA – reasons for differences being investigated
  - ALDEA models for vessel burst, fragments, blast from vented explosions may be able to be incorporated into HyRAM – assessing feasibility
  - ALDEA predicts higher concentrations at a given time in the case of leaks within enclosures – reasons for differences being investigated
  - Differences in cryogenic hydrogen models are being evaluated

Example results for vessel blowdown models

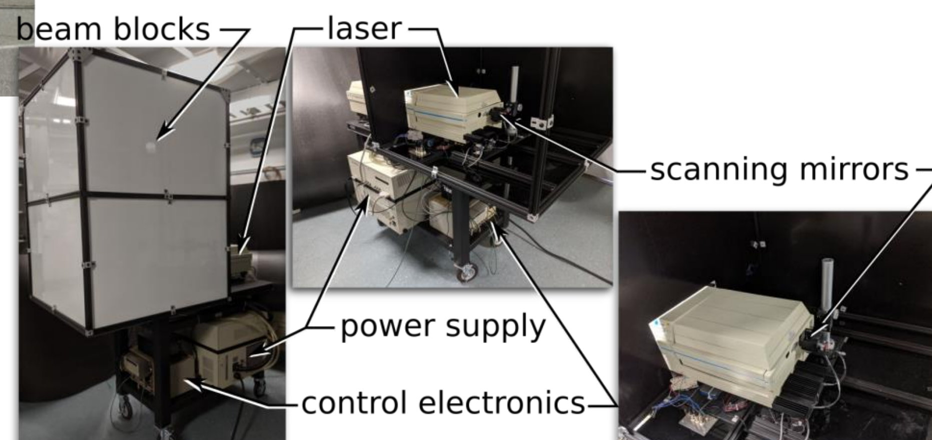
H2 140 L, 700 bar	AL results	AL tool	HyRAM results	HyRAM module
1 mm / time (s)	848	ALDEA-Blowdown	1073	Eng. Toolkit
2.4 mm / time (s)	147	ALDEA-Blowdown	186	Eng. Toolkit
4 mm / time (s)	53	ALDEA-Blowdown	67	Eng. Toolkit

Progress: A mobile laser scanning system has been developed, built and deployed (but not yet used)



Current status:

- All equipment onsite
- LH_2 tank filled
- Equipment (LH_2 pump, laser and diagnostic equipment at site) tested and operational
- Awaiting final safety signoff



Technology:

- Line-imaging of Raman scatter
- Laser to be rastered throughout plume to generate 3D picture of dispersion

Progress: A series of tests are planned, representative of a range of operations

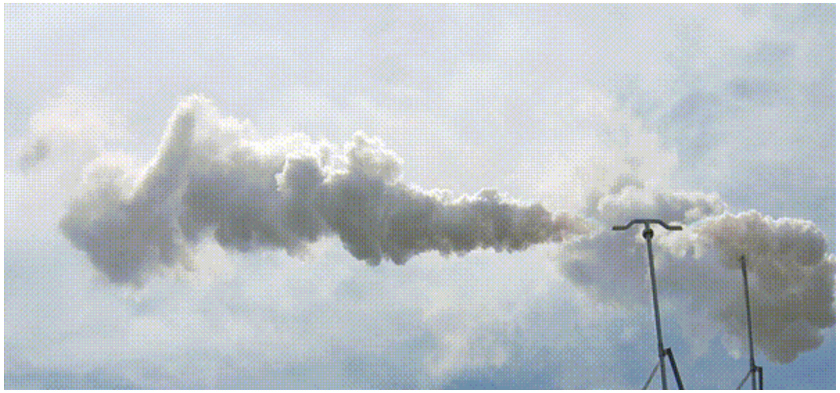
Notes: maximum pump flow rate: 120 kg/hr = 2 kg/min = 33 g/s,
normal boil-off is 4-8 kg/day

description	flow rate (g/s)	duration (mins)	total H2 (kg)	Wind	Humidity	Purpose	Note
high-flow warm plume dispersion	16.67	30	30	low (< 5 MPH)	any	validate diagnostic (high flow-rate/concentration, no condensation)	Warm H2 to as high a T as possible, repeat until diagnostic deemed ready
high flow cold dispersion	16.67	30	30	low (< 5 MPH)	low	simulate vent release during transfer	Possibly repeat with high and low ambient temperatures
high flow cold dispersion	16.67	30	30	high (> 5 MPH)	low	simulate vent release during transfer	
high flow cold dispersion	16.67	30	30	low (< 5 MPH)	high	simulate vent release during transfer	
high flow cold dispersion	16.67	30	30	high (> 5 MPH)	high	simulate vent release during transfer	
simulated high-boiloff	0.56	30	1	low (< 5 MPH)	low	simulate high level of boiloff	Possibly repeat with high and low ambient temperatures. May need to precool vent lines with higher flows before reducing flow rate.
simulated high-boiloff	0.56	30	1	high (> 5 MPH)	low	simulate high level of boiloff	
simulated high-boiloff	0.56	30	1	low (< 5 MPH)	high	simulate high level of boiloff	
simulated high-boiloff	0.56	30	1	high (> 5 MPH)	high	simulate high level of boiloff	
normal boiloff	0.07	30	0.125	low (< 5 MPH)	any	normal boilff measured by meter	May need to scrap if diagnostic not sensitive enough.
normal boiloff	0.07	30	0.125	high (> 5 MPH)	any	normal boilff measured by meter	

4 weather conditions: high and low wind, high and low humidity. Each day when the weather is right, can perform 4 experiments: high-flow cold dispersion, simulated high boil-off, and normal boil-off. This means there are 4 actual days of testing (8 if we do high and low ambient temperatures). If everything goes right, we need approximately 160 kg/H2.

Progress: We will be able to answer key questions at the end of the campaign

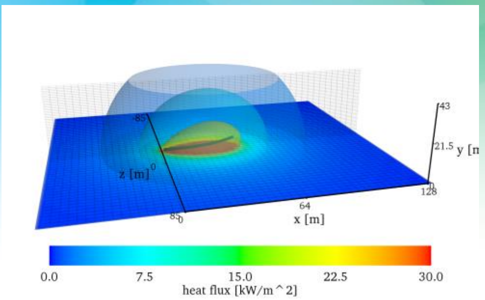
- Does wind cause channeling and increase the distance to the LFL, or improve mixing to decrease the distance to the LFL?
- Does high humidity cause increased buoyancy due to the energy transfer from the condensation of moisture, or does the condensed moisture drag the hydrogen down so it's less buoyant?
- Is the hydrogen concurrent with the condensed moisture? Does concurrency depend on the humidity?
- Is our model accurate enough for risk calculations for larger releases?



Response to previous year reviewer's comments

- This project was not reviewed last year

Collaboration & coordination



For the benchmarking HyRAM task:

- AL: Select up to 10 scenarios, use internal risk tool to analyze scenarios, compare with HyRAM results, review final report.
- SNL: Analyze up to 10 scenarios with HyRAM and compare results, develop final report.

For the experimental tasks:

- AL: Support experimental design by providing industry experience, conduct periodic advisory panel meetings, review final report.
- CGA G-5.5 testing task force: Coordinate LH2 vent stack flame experiments with industrial and national laboratory partners.
- SNL: Develop optical diagnostic to measure dispersion of cold gaseous hydrogen from a LH2 release plume in at least 2-dimensions,design validation testing, develop final report.

HyRAM HYDROGEN RISK ASSESSMENT MODELS

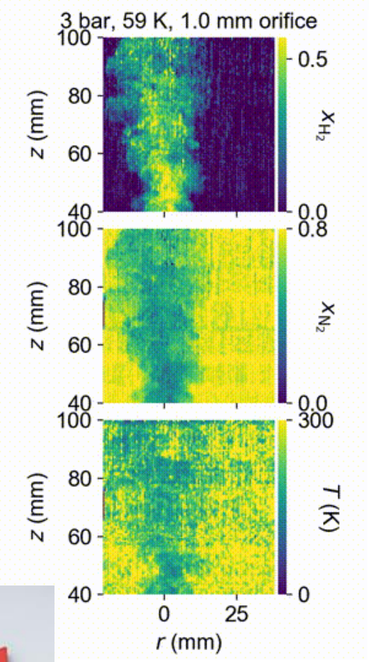
Remaining challenges & barriers

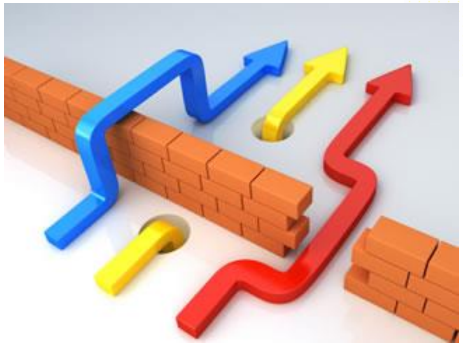
Task 1 - Benchmarking HyRAM:

- Cryogenic hydrogen models are not validated well enough to warrant presenting results publically

Task 2 - Experimental work:

- Final safety approval for experiments at LLNL are imminent
- CGA G-5.5 led ignited releases have been indefinitely delayed due to pandemic
- Challenge to translate experimental results into proposal(s) for NFPA 2





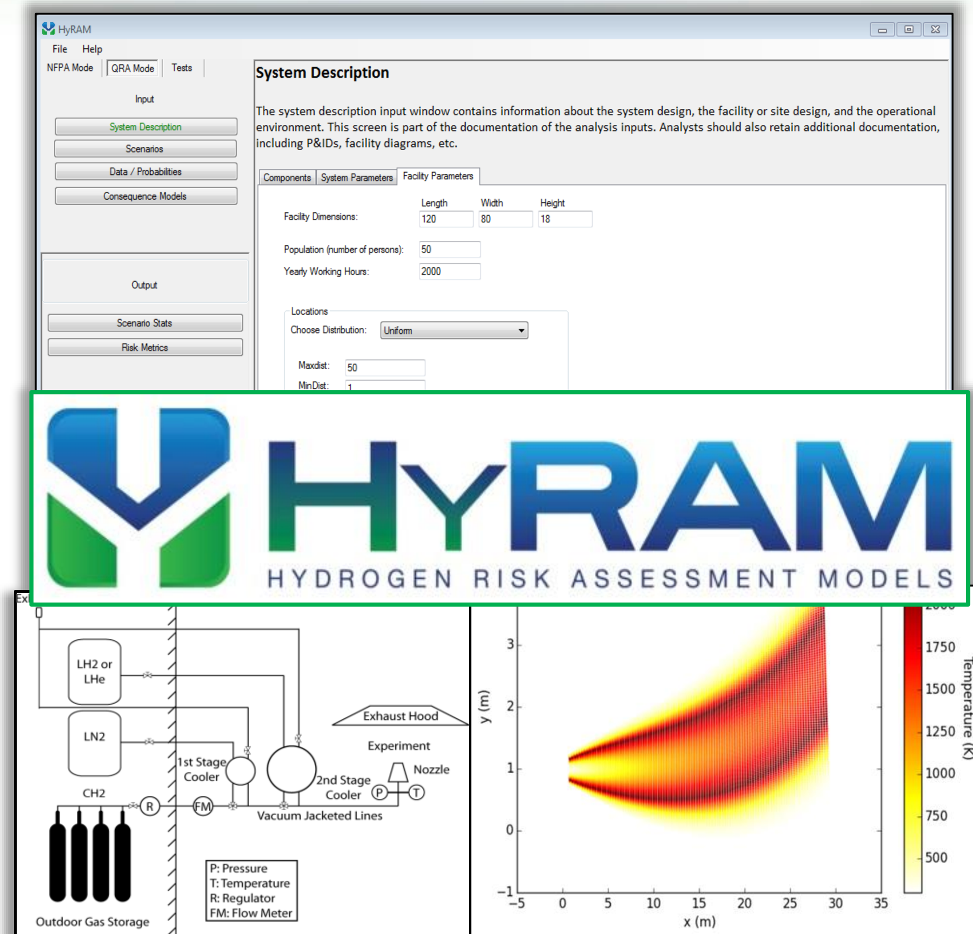
Proposed future work

- Finalize and publish report on HyRAM - ALDEA comparison
- Update HyRAM with lessons-learned from comparisons
- Perform planned vent-stack dispersion experiments at LLNL liquid hydrogen pad
- Provide measurement and analysis support of CGA G-5.5 testing task force data collection on H2 vent stack flame experiments
- Refine characterization of LH2 releases with validated cold plume release and provide sound, scientifically based revised bulk LH2 separation distances in NFPA 2/55

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



Current release is version 2.0

Summary

Relevance: Build validated H_2 behavior physics models and QRA tools that enable industry-led C&S revision

Approach:

- Benchmark HyRAM against Air Liquide models (ALDEA) and update models where issues are seen
- Measure unignited dispersion at LLNL LH_2 research facility using custom diagnostic and support CGA G-5.5 testing task force experiments measuring LH_2 vent stack flames and, using results to validate models
- Generate proposal(s) for science based LH_2 setback distances in NFPA 2/55

Progress & Accomplishments:

- Common scenarios were identified and simulated with ALDEA and HyRAM
- Good agreement was seen for free jets and flames
- Differences in blowdown and other models being investigated
- Report drafted
- Diagnostic designed, constructed and deployed
- Test plan in place for unignited dispersion measurements

Future work:

- Finalize and publish report on modeling comparison
- Perform experiments and report on results
- Provide proposal(s) to NFPA 2/55 for liquid hydrogen separation distances

Technical Back-Up Slides

HyRAM: Making hydrogen safety science accessible through integrated tools

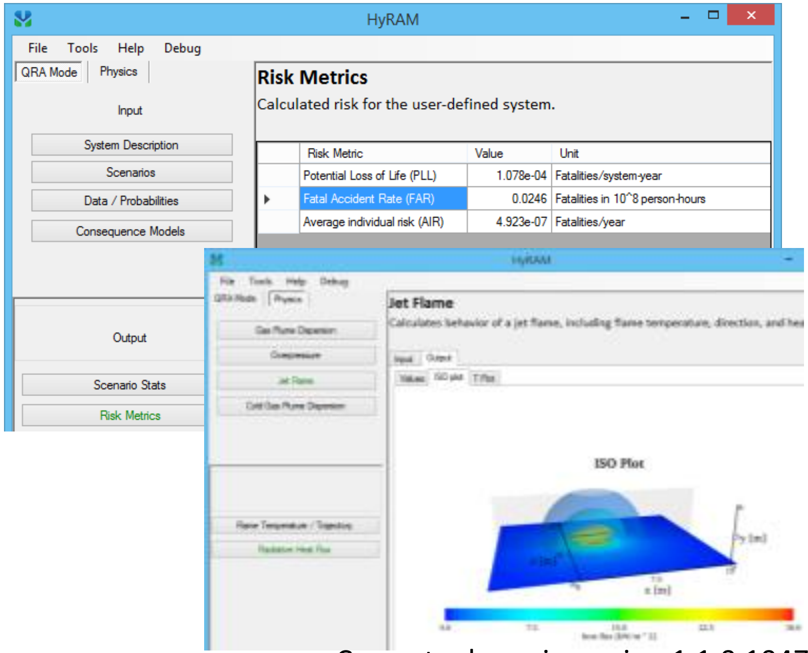
First-of-its-kind integration platform for state-of-the-art hydrogen safety models & data - **built to put the R&D into the hands of industry safety experts**

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



Current release is version 1.1.0.1047

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