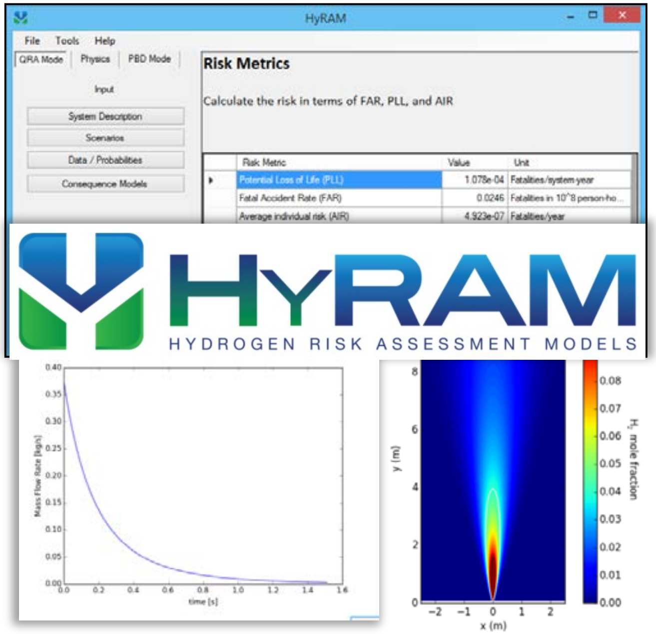
# Hydrogen Quantitative Risk Assessment




**PI: Katrina M. Groth**

Team: Myra Blaylock, Andrew Clark, Ethan Hecht, Alice Muna, John Reynolds PM: Chris LaFleur

Sandia National Laboratories

Livermore, CA and Albuquerque, NM

Project # SCS011

*2016 DOE Hydrogen and Fuel Cells Annual Merit Review*

June 7, 2016

# Overview

## Timeline

- Project start date: Oct. 2003
- Project end date: Sept. 2016*

  * Project continuation and direction determined by DOE annually.

## 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

L. Usage and Access Restrictions – parking structures, tunnels and other usage areas

## Budget

- FY15 DOE Funding: $370k
- Planned FY16 DOE Funding: $370k
- Total DOE Project Value: $23M*

*(*Total funding includes SCS#010, SCS#011 and SCS#025: Behavior, Risk and Infrastructure/Code program elements)*

## Partners

Industry & research collaborators:
Linde, Gexcon, PNNL, NREL,

SDO/CDO participation:
NFPA 2, ISO TC197 WG24, H2USA, CaFCP, FPRF

International engagement:
HySafe, IEA HIA Task 37

# Relevance

Objective: Provide a **science & engineering** basis for assessing safety (risk) of $H_2$ systems and **facilitate use of that information** for revising RCS and permitting stations.

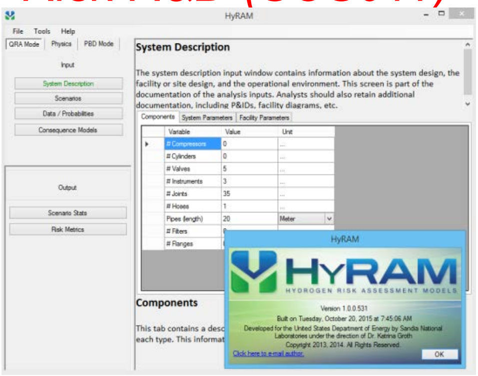
| Barrier from 2013 SCS MYRDD | SNL Goal |
|---|---|
| A. Safety Data and Information: Limited Access and Availability | Develop & validate $H_2$ behavior physics models to address targeted gaps in knowledge |
| F. Enabling national and international markets requires consistent RCS<br>G. Insufficient 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 (physics and QRA). |
| L. Usage and Access Restrictions – parking structures, tunnels and other usage areas | Develop $H_2$-specific QRA [Quantitative Risk Assessment] tools & methods to support RCS decisions and to enable Performance Based Design (PBD) code-compliance option. |

# Relevance: Bringing scientific rigor, into decision-making for SCS

- **Successful application of SNL models & approach in $H_2$ RCS:**
  - **NFPA2 Ch. 7**: Established $GH_2$ separation distances (SAND2012-10150)
  - **NFPA2 Ch. 10**: Calculated risk from indoor fueling; identified ambiguity in requirements (SAND2012-10150)
  - **NFPA2 Ch. 5**: Enabling *Performance-based* compliance option (SAND2015-4500)
  - **ISO DTR-19880-1 Ch. 4**: Developing generalized approach for defining specific mitigations (e.g., safety distances) using regional criteria
- **Usage in current RCS activities**
  - **NFPA 2:** $LH_2$ separation distances , revision of $GH_2$ separation distances
  - **ISO DTR-19880-1:** develop DIS from the TR; develop of regional mitigation examples using SNL approach
- **Future areas of application of the work:**
  - NFPA and ISO code revisions, e.g., enclosures
  - Design insight, i.e. comparison of the safety impact of different designs; identification of top risk/reliability drivers

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

## *Risk R&D (SCS011)*




***Develop integrated methods and algorithms***

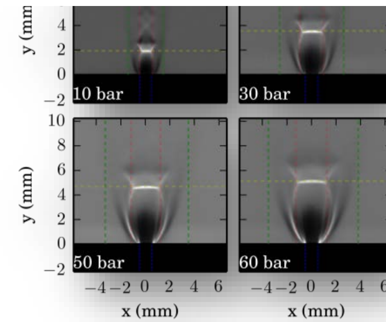
for enabling consistent, traceable and rigorous QRA

## *Application in C&S (SCS025)*

***Apply QRA & behavior models to real problems***

in hydrogen infrastructure and emerging technology

## *Behavior R&D (SCS010)*




***Develop and validate scientific models***

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

Enabling methods, data, tools for $H_2$ safety & RCS

# Approach / FY15-16 Milestones

| | Completion date or status |
|---|---|
| **Develop the HyRAM toolkit/platform** to facilitate use of hydrogen safety research in industry-led safety analyses | |
| • Develop & integrate modules for overpressure, layering, gas plume behavior models<br>• Go/no go – negotiate license conditions to enable integration (in FY17) of IRIS software (Univ. of MD) for expanded QRA functions<br>• Testing, bug fixes, and user engagement | Dec 2015<br><br>GO<br><br>Ongoing / as needed |
| **Release HyRAM & publish documentation** | |
| • Publish technical reference report on HyRAM V1.0 algorithms<br>• Obtain copyright & licenses to enable public distribution; build website for users to download HyRAM<br>• Compile HyRAM V1.0 release version<br>• Begin public release announcements<br>  • "Soft release" via word-of-mouth<br>  • Official release at DOE webinar | Nov 2015<br>Feb 2016<br><br>Mar 2016<br><br>Mar 2016<br>Apr. 26, 2016 |

# HyRAM: Making hydrogen safety science accessible through integrated tools

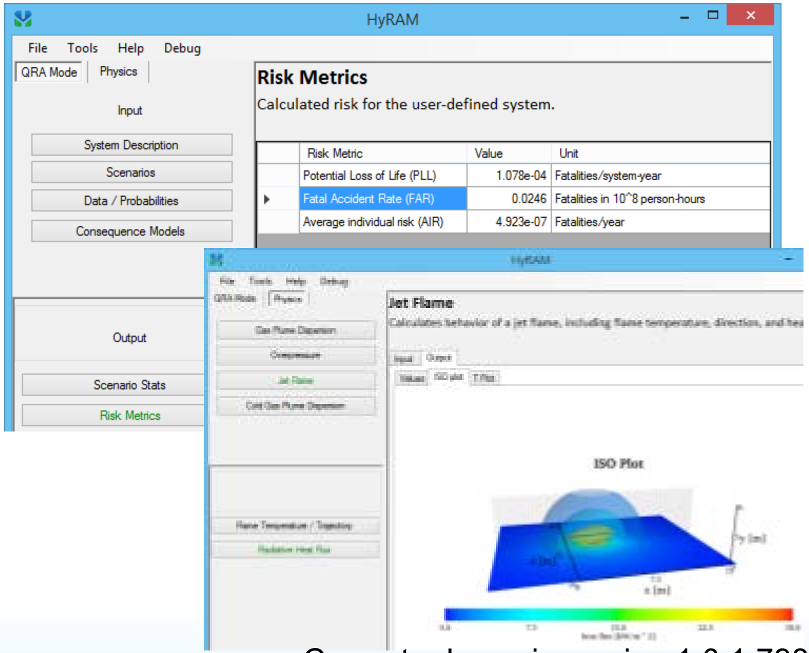
**First-of-its-kind integration platform** for state-of-the-art hydrogen safety models & data - **built to put the R&D into the hands of industry safety experts**

**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



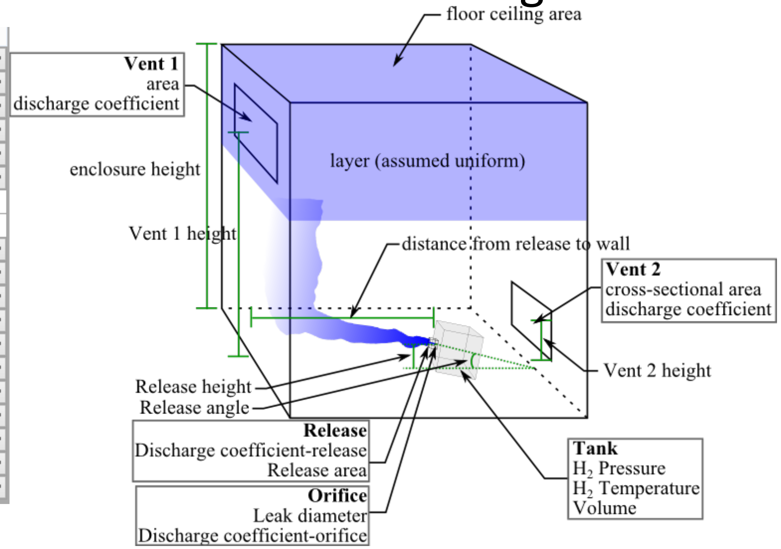

Current release is version 1.0.1.798

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

# Accomplishment: New module - overpressure & layer

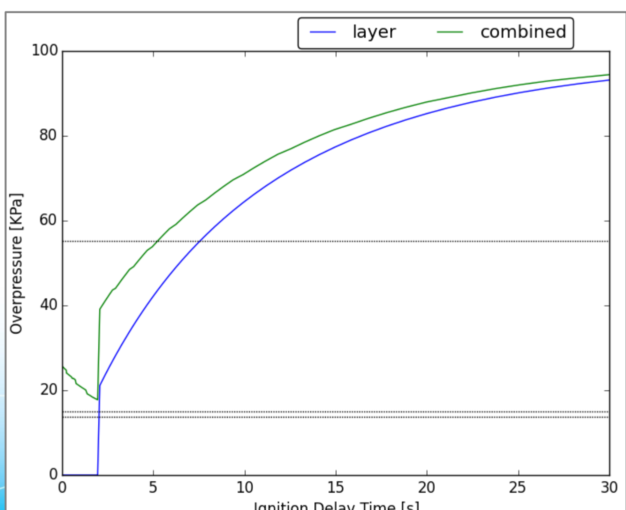
## **Input:** Release conditions and enclosure configuration

| Variable | Value | Unit |
|---|---|---|
| Ambient Pressure | 101325 | Pa |
| Ambient Temperature | 288.15 | Kelvin |
| H2 Tank Pressure | 70 | MPa |
| H2 Tank Temperature | 287.8 | Kelvin |
| H2 Tank Volume | 0.00363 | CubicMeter |
| Leak Diameter | 0.1 | Centimeter |
| Discharge Coefficient-Orifice | 0.61 | ... |
| Discharge Coefficient-Release | 1 | ... |
| Release Area | 0.01716 | SqMeters |
| Release Height | 0.2495 | Meter |
| Enclosure Height | 2.72 | Meter |
| Floor/Ceiling Area | 16.72216 | SqMeters |
| Distance from Release to Wall | 2.1255 | Meter |
| Vent 1 Cross-Sectional Area | 0.090792027688... | SqMeters |
| Vent 1 Vent Height from Floor | 2.42 | Meter |
| Vent 2 Cross-Sectional Area | 0.00762 | SqMeters |
| Vent 2 Height from Floor | 0.044 | Meter |
| Vent Volumetric Flow Rate | 0 | CubicMeters... |
| Angle of Release (0=Horz.) | 0 | Degrees |




- Enables calculation of consequences inside of enclosures.
- Insight into enclosure design, effectiveness of mitigations

## **Output:** Overpressure (ignited) & Height of accumulated layer (unignited)

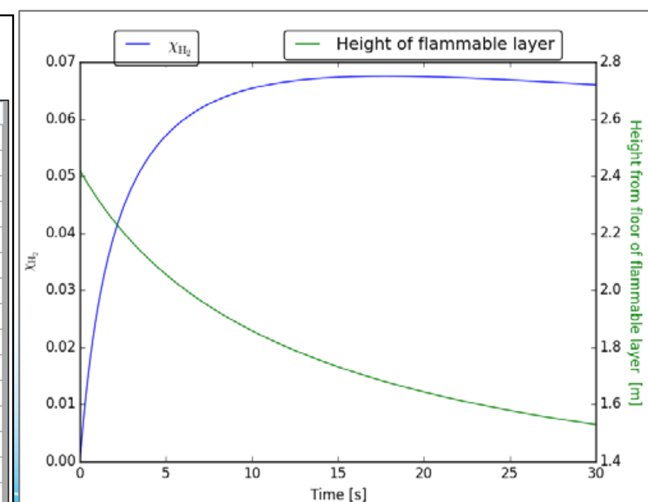



Maximum pressure (Pa): 94418.2835711473

Time this occurred (seconds): 30

| Time | Pressure |
|---|---|
| 1 | 2.089E+004 |
| 2 | 2.670E+004 |
| 3 | 4.446E+004 |
| 4 | 4.957E+004 |
| 5 | 5.409E+004 |
| 6 | 5.841E+004 |
| 7 | 6.210E+004 |
| 8 | 6.528E+004 |
| 9 | 6.849E+004 |
| 10 | 7.105E+004 |
| 11 | 7.365E+004 |
| 12 | 7.595E+004 |
| 13 | 7.788E+004 |
| 14 | 7.982E+004 |
| 15 | 8.155E+004 |
| 16 | 8.294E+004 |

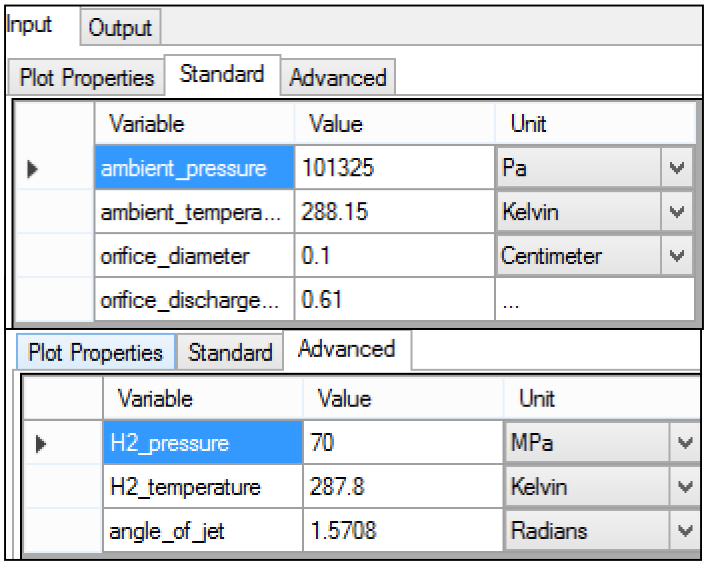
| Depth | Concentration |
|---|---|
| 0.39711803 | 2.622E-002 |
| 0.47903418 | 3.974E-002 |
| 0.54935446 | 4.791E-002 |
| 0.61057559 | 5.331E-002 |
| 0.66450595 | 5.707E-002 |
| 0.71242342 | 5.979E-002 |
| 0.75545507 | 6.181E-002 |
| 0.79417555 | 6.332E-002 |
| 0.82938139 | 6.447E-002 |
| 0.86156604 | 6.535E-002 |
| 0.89098494 | 6.601E-002 |
| 0.91810608 | 6.651E-002 |
| 0.94312791 | 6.688E-002 |
| 0.96641626 | 6.714E-002 |
| 0.98800216 | 6.733E-002 |
| 1.00805418 | 6.744E-002 |



# Accomplishment: New module - gas plume dispersion

## Input

- Release size & conditions


Input | Output

Plot Properties | Standard | Advanced

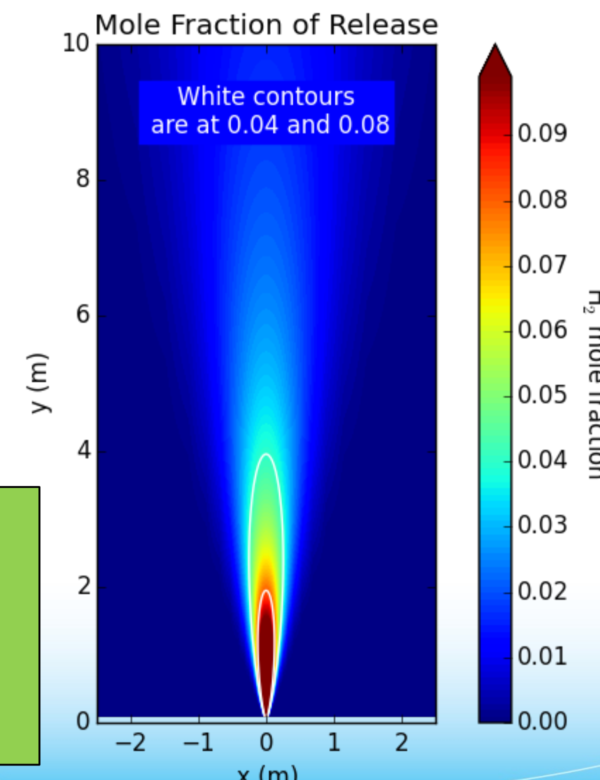
| Variable | Value | Unit |
| --- | --- | --- |
| ambient_pressure | 101325 | Pa |
| ambient_tempera... | 288.15 | Kelvin |
| orifice_diameter | 0.1 | Centimeter |
| orifice_discharge... | 0.61 | ... |

Plot Properties | Standard | Advanced

| Variable | Value | Unit |
| --- | --- | --- |
| H2_pressure | 70 | MPa |
| H2_temperature | 287.8 | Kelvin |
| angle_of_jet | 1.5708 | Radians |

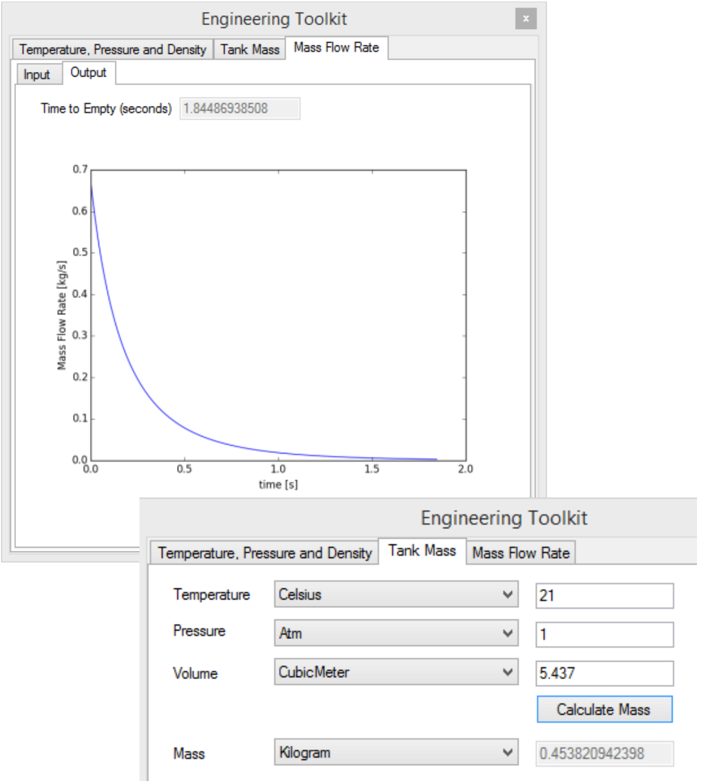
## Output

- Gas concentration at different distances - direct analog to NFPA2 safety distance work




- Enables revision of NFPA 2 safety distances to address conservatisms introduced by selection of 4% concentration as a harm criterion
- Illustration shows distance reduction that could be achieved by using 8% criterion rather than 4%.

# Accomplishment: Improvements to existing HyRAM features - enabled by testing




## Testing: Currently focusing on usability & functionality.

- Internal testers plus alpha testers from 8 external partners (see collaborations slide);
- 29 release candidate versions (23 internal test versions; 4 alpha releases, 2 public releases)

## New/improved features:

- **Reconfigured GUI for jet flame module** – streamlined input and output screens and added input options in response to user feedback
- **New *Engineering Toolkit* feature** to facilitate simple calculations, e.g. density, tank volume/mass conversion, tank blowdown rate
- **New GUIs in QRA mode** – occupant / target position, master input editor

- User feedback and subsequent software improvements are crucial to ensure creation of enabling tools & guidance.

# Accomplishment: Published HyRAM user guide and algorithm report

- **Technical reference manual and papers** documenting algorithm, models, approach, assumptions, and references for HyRAM V1.0.
  - KM Groth, ES Hecht & JT Reynolds. *Methodology for assessing the safety of Hydrogen Systems: HyRAM 1.0 technical reference manual.* SAND2015-10216, Nov, 2015.
  - KM Groth and ES Hecht. HyRAM: A methodology and toolkit for Quantitative Risk Assessment of Hydrogen Systems. ICHS 2015.
- User guides
  - KM Groth, HR Zumwalt, A Clark. *HyRAM V1.0 User Guide*. Sandia National Laboratories, Albuquerque, NM, March, 2016.

HyRAM publications are available for download on hyram.sandia.gov

- Documentation is essential for traceability, peer review, and verification of HyRAM methods, models and data.
- *Reduces industry burden* - allows industry to focus on getting safety insights rather than creating, validating, and documenting algorithms.

# Accomplishment: HyRAM enables development of codes & standards

- **Enabling performance-based design** of H2 fueling stations
  - SNL leads pilot application of PBD for H2; Published design brief template (SAND2015-4500)
  - HyRAM used to: calculate baseline risk metrics for a generic station, and provide a platform for industry to compare specific design proposals to the baseline
- **ISO DTR-19880-1** (Accepted by all voting countries Oct. 2015).
  - Sub-team co-lead by SNL and Air Liquide wrote Chapter 4 (safety methodology and mitigations) based on HyRAM methodology
  - Countries follow the same general method, and document country-specific assumptions and model choices; HyRAM enables rapid comparison of the impact of assumptions, data, & modeling choices
- **NFPA 2** – (In revision for 2019)
  - HyRAM being used to revise of gaseous hydrogen separation distances (Ch. 7); models being developed to enable revision of liquid separation distances using same methodology

See SCS025 for additional detail

- HyRAM enables harmonization of safety methodology used in ISO & NFPA 2
- HyRAM provides a platform for quantifying risk values for SCS activities:
  - Risk-informed code development (e.g., NFPA safety distances)
  - Risk-equivalent code compliance (i.e., performance-based),
  - Risk-based codes (e.g., Dutch approach to SCS)

# Collaborations: Partners, RCS participation & international engagement

- **Linde -** Signed CRADA - In-kind support, data exchange for QRA tool, PBD activities, LH2 laboratory
- **Gexcon -** Technical exchanges on validation activities for physics models, integration of safety methodology approaches; In-kind support - provided FLACS research license
- **PNNL -** Technical exchanges on PBD;QRA; Hydrogen Safety Panel
- **NREL -** Technical exchanges on PBD; QRA
- **HySafe -** Technical exchanges on safety methodology; QRA toolkits
- **NFPA 2 -**Liquid separation distances task group
- **ISO TC197 WG24-** SNL co-leads sub-team on safety methodology
- **IEA HIA Task 37 -**SNL leads sub-task on Safety Integration Toolkits;
- **H2USA -** Various working groups
- **CaFCP Auto OEM group; NFPA FPRF; -** CRADA to support research on LH2 releases, QRA, and PBD

# Collaborations: HyRAM users

## V1.0alpha (2/2015 - 2/2016)

- Limited/restricted release to selected stakeholders **for testing & feedback purposes only**
- Required a signed non-disclosure agreement (NDA)
- Invited 24 stakeholders, received signed NDA from 7 partners:
  - PNNL
  - NREL
  - Zero Carbon Energy Solutions
  - GWS Solutions
  - AVT (CA)
  - ITM Power (UK)
  - Shell (UK)

## V1.0 (3/1/2016 – future*)

- Anticipating significant increase in downloads after webinar in April 2016.
- 7 external users, including from:
  - PNNL
  - ZCES
  - Linde
  - Paul Scherrer Inst. (CH)

*stats reflect period through 3/29/2016

# Technology transfer activities

- Significant efforts to ensure that results are published & available
  - 8 presentations, 12 papers (journal, conference, or technical report); additional publications by SCS010 and SCS025 and in previous years
  - Developed website for distributing HyRAM software and documents: http://hyram.sandia.gov
- Project adds intellectual value to the code decision process
  - HyRAM provides means for translating the science (from SCS010 and SCS011) into meaningful decision support for codes (SNL activities under SCS025)
- HyRAM V1.0 software is being made publically available – free download; flexible licensing terms (see website for both)
  - Supersedes Jan 2015 1.0alpha release (restricted to use by alpha testers with a Non-Disclosure Agreement (NDA) with Sandia)

# Remaining challenges & barriers

- **Ongoing need for safety data and models** (barriers A, G)**:**
  - **Validated physics models for hydrogen behaviors**, including: liquid/cryogenic release behavior; deflagration (unconfined) and detonation models, flow/flame surface interactions, barrier walls, ignition,
  - **Operating experience or other information to generate data/probabilities** for hydrogen system component failures, leak frequencies, detection effectiveness, etc.
- **Need for additional features and models** to enable deeper system-specific insights to enable overcoming station-siting barriers (barrier L)
  - **Uncertainty & sensitivity analysis capabilities**
  - **Higher fidelity and depth of QRA models** (e.g., Fault Trees, Event Sequence Diagrams, importance measures) - Capabilities to allow users to edit scenarios, root cause models
  - **Source code for validated physics models**
- **HyRAM V1.0 is a research prototype. Need external support and partners** to lead or support formal software activities, validation, testing, training, etc.

Note: HyRAM does not say that a system is/is not safe, because safety is not an equation.

*"We cannot replace difficult ethical and political deliberations with a mathematical one-dimensional formula"* (Aven, *Foundations of Risk Analysis, 2003*).

# Proposed future work

- Rest of FY16:
  - Source code changes to bring overpressure model into QRA mode
  - Scoping algorithms for uncertainty analysis in QRA mode
  - Add source code for two-zone notional nozzle model (from SCS010)
- FY17:
  - Add source code for cold-plume model (SCS010)
  - Begin software changes to integrate IRIS software to allow users to edit scenarios, root cause models in QRA mode (First stages of V2.0)
  - Establishing process to enable external R&D community to contribute models and data, i.e. as plug-ins
  - Develop tests and scripts for code verification

**Long-term vision** – *Partner with stakeholders* to create a fully configurable, tested software product available for users to calculate hydrogen risk values and consequences; Able to support a wide range of activities within RCS and system design.

# Response to last year's Reviewer's comments

- *AMR2015 comment: "The presenter said, for example, that selected ISO TC 197 WG 24 partners are acting as alpha testers. Entities are required to agree to so many legal conditions before receiving permission to access HyRAM that not many international players will be able to do so. For HyRAM to have a chance to become the reference tool for design, it would be better to follow a much more public distribution to allow independent verification and validation"*
  - *We recognize that the legal agreement was a significant challenge for some stakeholders. The legal agreement necessary in 2015 due to alpha testing activities on HyRAM non-public versions. During 2016 we revised legal agreements and licenses to enable public release. The public release of HyRAM V1.0 is now available at hyram.sandia.gov*
- *AMR2015 comment: "Next year, the presenter should disclose additional details on how data on real component performance is gathered and elaborated in HyRAM..."*
  - HyRAM contains data and models from published sources. In FY16 we published the HyRAM technical reference manual which provides references to all data sources. Specific information about component performance data would be found in the original publication. HyRAM allows users to overwrite the default data with their own input (i.e., company-specific data, or data from non-public sources).
- *AMR2015 comment: The project should include uncertainty analysis in the HyRAM's calculated risks: Potential Loss of Life, Fatal Accident Rate, and Average Individual Risk.*
  - We have added this to the scope. We are currently exploring algorithms and foresee having this capability sometime in FY17 or 18.
- *AMR2015 comment: If not heavily tested and validated, the tool risks remaining a toy for first-stage designers. The presentation stated that all the phenomena already considered in Hydrogen Risk Assessment Models (HyRAM) have been validated. It is highly probable that 10 minutes was not enough time to give full demonstration of this fact, but that should occur in the future.*
  - HyRAM V1.0alpha contained models for two phenomena: gas plume and jet flame behavior. Previous activities at Sandia (SCS010) conducted experimental validation on the hydrogen plume and jet flame models during model development. Details of that validation are available in the original publications on those models – the citations are available in the HyRAM technical reference report.
  - The long-term vision for HyRAM includes formal software development, testing and quality activities. In this year's presentation I clarified that external stakeholders must lead this process because these activities fall outside the mission of the national labs.
  - To make meaningful progress on barriers F and L, the first stage designers need tools.

# Summary

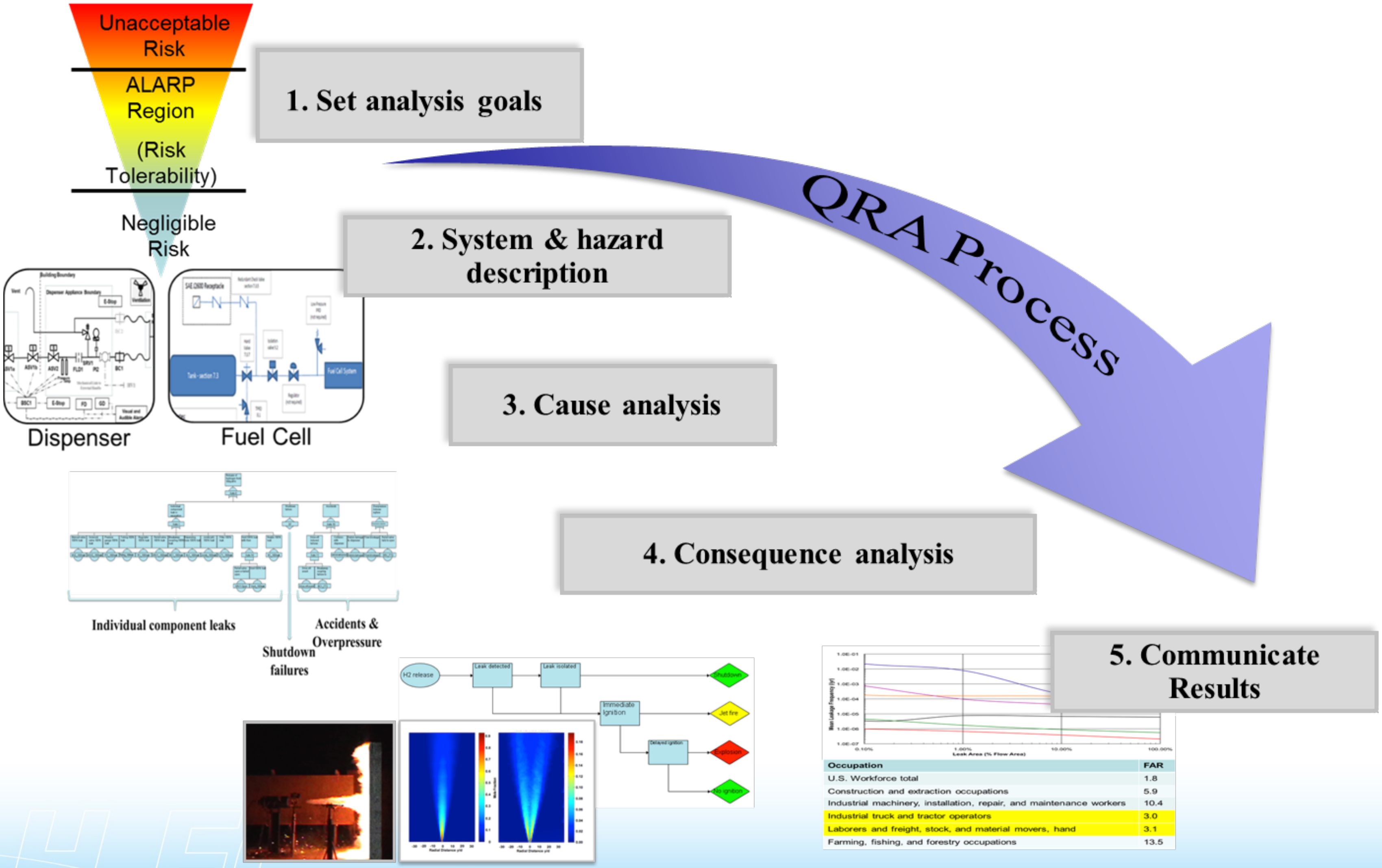
- **Three-pronged R&D approach:** two R&D activities (SCS011, 010) feeding C&S development (SCS025)
  - Provide science & engineering basis for assessing safety (risk) of H2 systems and facilitate use of that information in RCS and permitting
  - Coordinated activities ensures: Accelerated transfer of 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:** HyRAM V1.0 public release, New features (Engineering Toolkit, gas plume model, overpressure & layer model), Published HyRAM V1.0 algorithm report & user guide, Used HyRAM in RCS activities (PBD report, NFPA 2, ISO TR-19980-1)
- **Future Work**: Add features to expand fidelity, depth, and usability of QRA mode; Write source code for new physics models; Testing and validation; Targeted RCS engagement to reduce barriers

# Technical Back-Up Slides

# Elements of QRA quality

- **Repeatability**
  - Defined objectives and scope;
  - Clear definitions of failure modes, consequences, criteria, models, and data
  - Document the system, assumptions,
- **Validity & Verifiability**
  - Data, models, system, and analysis must be sufficiently documented for a peer reviewer to evaluate assumptions, completeness, etc.
  - Use experimentally validated models (as available) and published models and data.
- **Comparability**
  - Necessitates flexible modeling tools, documentation of methodology
- **Completeness**
  - Ability to update models as knowledge improves
  - Ensure that analyzed system matches the system as built and operated

# Steps of QRA Approach




| Occupation | FAR |
|---|---|
| U.S. Workforce total | 1.8 |
| Construction and extraction occupations | 5.9 |
| Industrial machinery, installation, repair, and maintenance workers | 10.4 |
| Industrial truck and tractor operators | 3.0 |
| Laborers and freight, stock, and material movers, hand | 3.1 |
| Farming, fishing, and forestry occupations | 13.5 |

# Major elements of HyRAM software

## QRA Methodology

- Risk metrics calculations: FAR, PLL, AIR
- Scenario models & frequency
- Release frequency
- Harm models

## Generic freq. & prob. data

- Ignition probabilities
- Component leak frequencies (9 types)

## Physics models

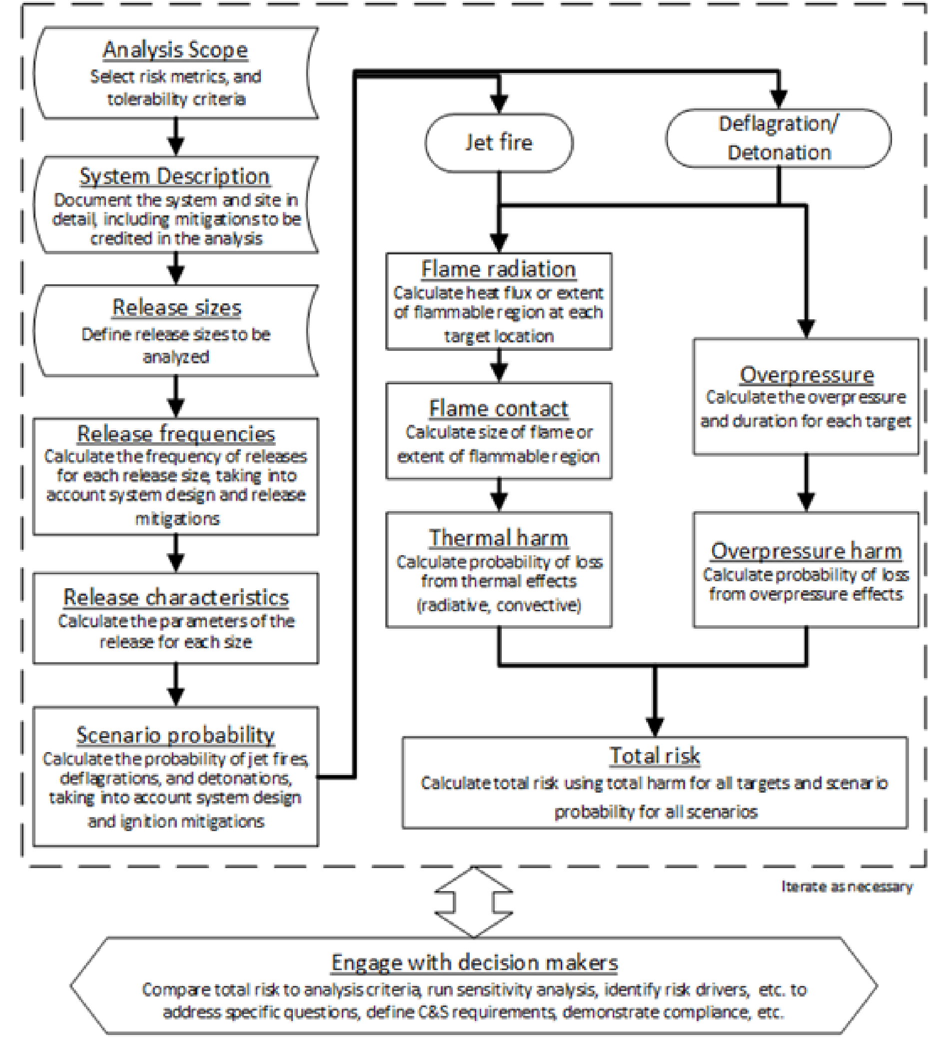
- Properties of Hydrogen
- Unignited releases: Orifice flow; Notional nozzles; Gas jet/plume; Accumulation in enclosures
- Ignited releases: Jet flames w/ and w/o buoyancy; overpressures in enclosures

## Mathematics Middleware

- Unit Conversion System
- Math.NET Numerics

## Documentation

- Algorithm report (SAND2015-10216)
- User guide (DRAFT/ / SAND2015-7380 R)



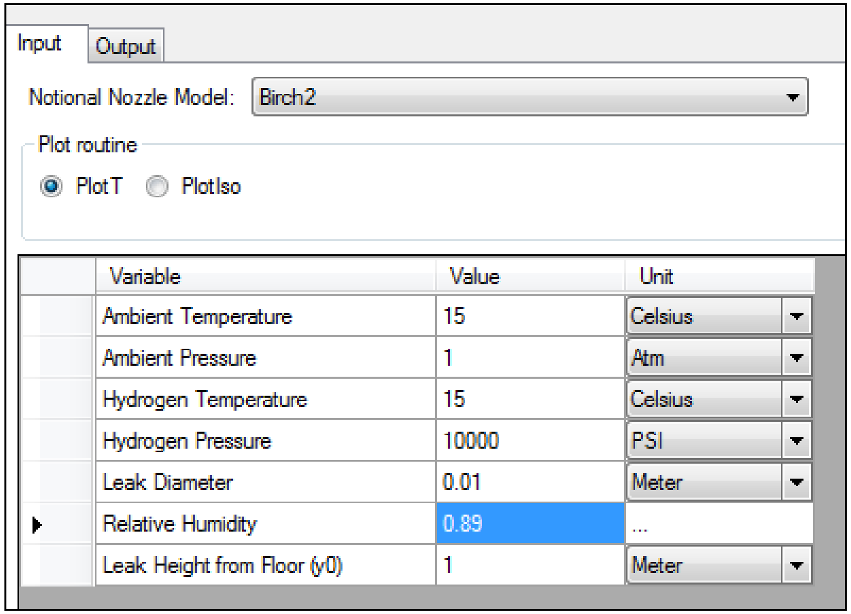

+ Free download via web

# Example HyRAM calculation: Jet Flame physics

**Consequence-only modeling**

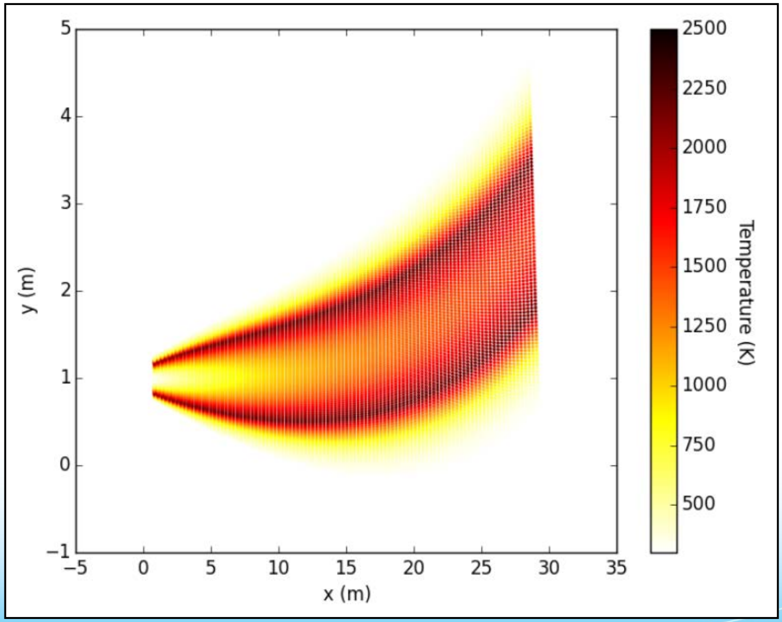
## Input

- Leak size and known conditions.




## Output

- Shows flame temperature at different distances -- direct analog to original safety distance work.



# Example HyRAM calculation: Full QRA

**Allows credit for mitigations that reduce likelihood of events & provides system-specific risk-reduction insight**

## Input

- System description (components, parameters, facility description)

Components | System Parameters | Facility Parameters

Piping | Vehicles

| Variable | Value | Unit |
|---|---|---|
| Pipe Outer Diameter | 0.375 | Inch |
| Pipe Wall Thickness | 0.065 | Inch |
| Internal Temperatu | | |
| Internal Pressure | | |
| External Temperatu | | |
| External Pressure | | |

Components | System Parameters | Facility Parameters

| Component | Count | Unit |
|---|---|---|
| # Compressors | 0 | ... |
| # Cylinders | 0 | ... |
| # Valves | 5 | ... |
| # Instruments | 3 | ... |
| # Joints | 35 | ... |
| # Hoses | 1 | ... |

Facility | Occupants

Input Details | Distribution

| Variable | Value |
|---|---|
| Population (Number of persons) | 50 |
| Working hours per year | 2000 |

## Output

- Total system risk
  - Enables comparisons, e.g. risk with vs. without gas detection

| Risk Metric | Value | Unit |
|---|---|---|
| Potential Loss of Life (PLL) | 4.500e-04 | Fatalities/system-year |
| Fatal Accident Rate (FAR)/100M exposed hours | 0.1027 | Fatalities in 10^8 person-ho... |
| Average individual risk (AIR) | 2.055e-06 | Fatalities/year |

| Risk Metric | Value | Unit |
|---|---|---|
| Potential Loss of Life (PLL) | 5.000e-04 | Fatalities/system-year |
| Fatal Accident Rate (FAR)/100M exposed hours | 0.1141 | Fatalities in 10^8 person-ho... |
| Average individual risk (AIR) | 2.283e-06 | Fatalities/year |

- Insight into risk drivers: scenario frequency & risk ranking

| Scenario | End State Type | Avg. Events/Year | PLL Contribution |
|---|---|---|---|
| 0.01pct Release | No Ignition | 0.03448206 | 0.00% |
| 0.1pct Release | No Ignition | 0.00495318 | 0.00% |
| 1pct Release | No Ignition | 0.00148741 | 0.00% |
| 10pct Release | No Ignition | 0.00116683 | 0.00% |
| 100pct Release | No Ignition | 0.00071471 | 0.00% |
| 0.01pct Release | Jet fire | 0.00025097 | 0.00 % |
| 0.01pct Release | Explosion | 0.00012448 | 0.01 % |
| 100pct Release | Jet fire | 0.00003669 | 0.00 % |
| 0.1pct Release | Jet fire | 0.00003605 | 0.00 % |
| 0.1pct Release | Explosion | 0.00001788 | 0.00 % |
| 100pct Release | Explosion | 0.00001770 | 95.15 % |
| 1pct Release | Jet fire | 0.00001083 | 0.00 % |
| 10pct Release | Jet fire | 0.00000849 | 0.00 % |
| 1pct Release | Explosion | 0.00000537 | 0.03 % |
| 10pct Release | Explosion | 0.00000421 | 4.81 % |