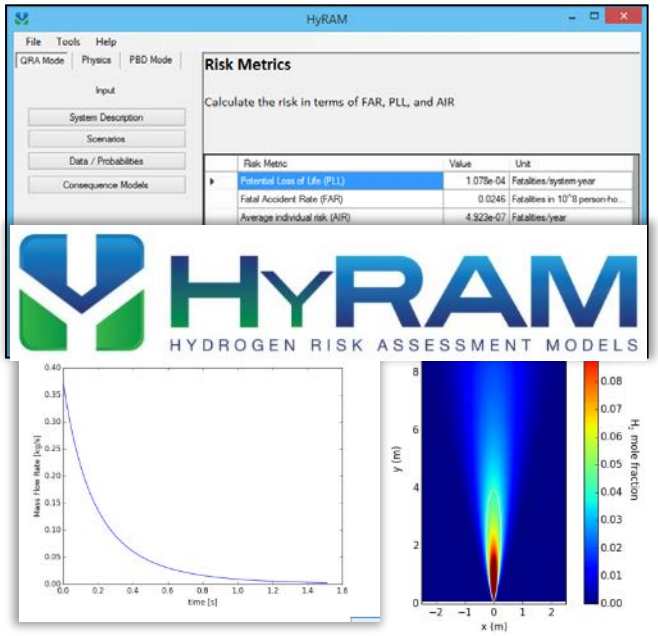
Overview of DOE Quantitative Risk Assessment and the Hydrogen Risk Assessment Model (HyRAM)



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Hydrogen and Fuel Cell Technical Advisory Committee
May 5, 2017

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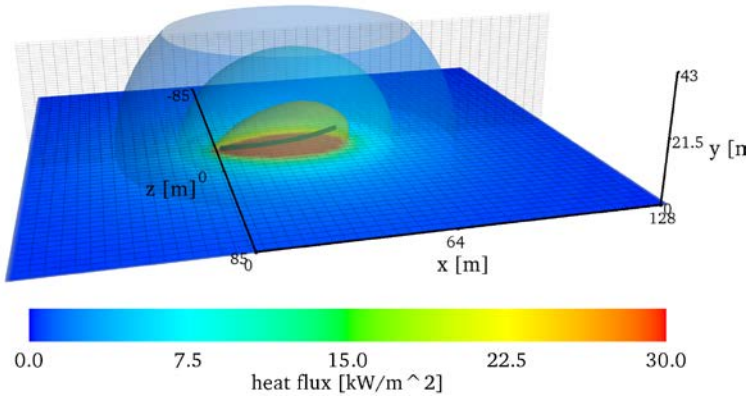
Project Approach: Coordinated activities that facilitate emerging hydrogen technologies

- Hydrogen Behavior
  - **Develop and validate scientific models** to accurately predict hazards and harm from liquid releases, flames, etc.
- Quantitative Risk Assessment, Tools R&D
  - **Develop integrated methods and algorithms** enabling consistent, traceable, and rigorous QRA (Quantitative Risk Assessment) for H_2 facilities and vehicles
- Enable Hydrogen Infrastructure through Science-based Codes and Standards
  - **Provide physics models and risk calculations to address real problems** in hydrogen infrastructure and emerging technology



HyRAM
HYDROGEN RISK ASSESSMENT MODELS

What is Risk Assessment?

Risk = "the potential for loss" (more specifically, "uncertainty about the potential for and severity of loss(es)"

Risk Analysis

- A process used to identify and characterize risk in a system
  - What could go wrong?
  - How likely is it?
  - What are the consequences?

Risk Management

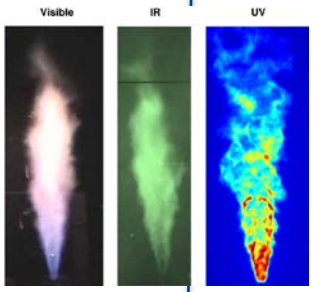
- Provide inputs to decision makers on:
  - Sources of risk
  - Strategies to reduce risk
  - Priorities

HyRAM uses the following risk equation to characterize the risk of hydrogen refueling systems:

$$Risk \propto \sum_{i,j,k} P(\text{Release}_i) P(\text{Ignition}_j | \text{Release}_i) P(\text{Hazard}_k | \text{Ignition}_j \cap \text{Release}_i) P(\text{Harm} | \text{Hazard}_k)$$

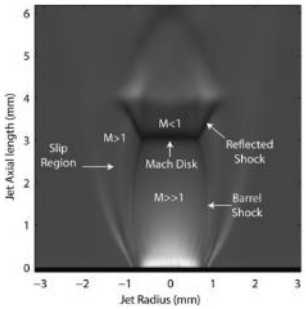
Hydrogen Behavior studies are at the foundation of HyRAM's consequence modeling capabilities

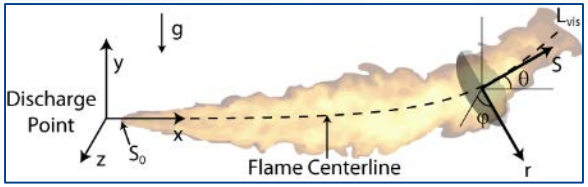
Radiative properties of H2 flames quantified



Barrier walls for risk reduction

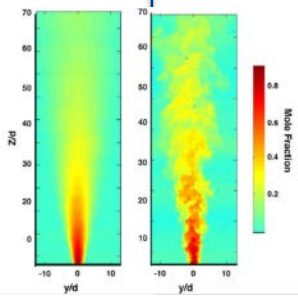
Ignition of under-expanded H2 jets





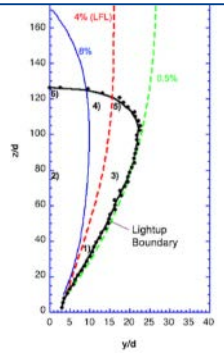
Buoyant jet flame model with multi-source radiation

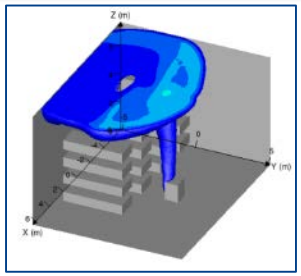
2005 2007 2009 2011 2013 2015 2017



Advanced laser diagnostics applied to turbulent H2 combustion

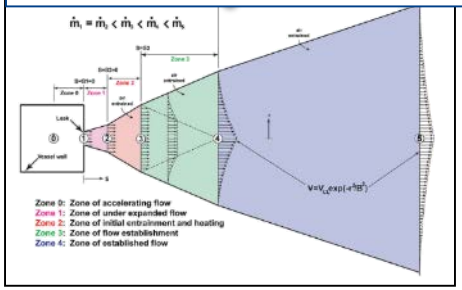
Ignition limits of turbulent H2 flows





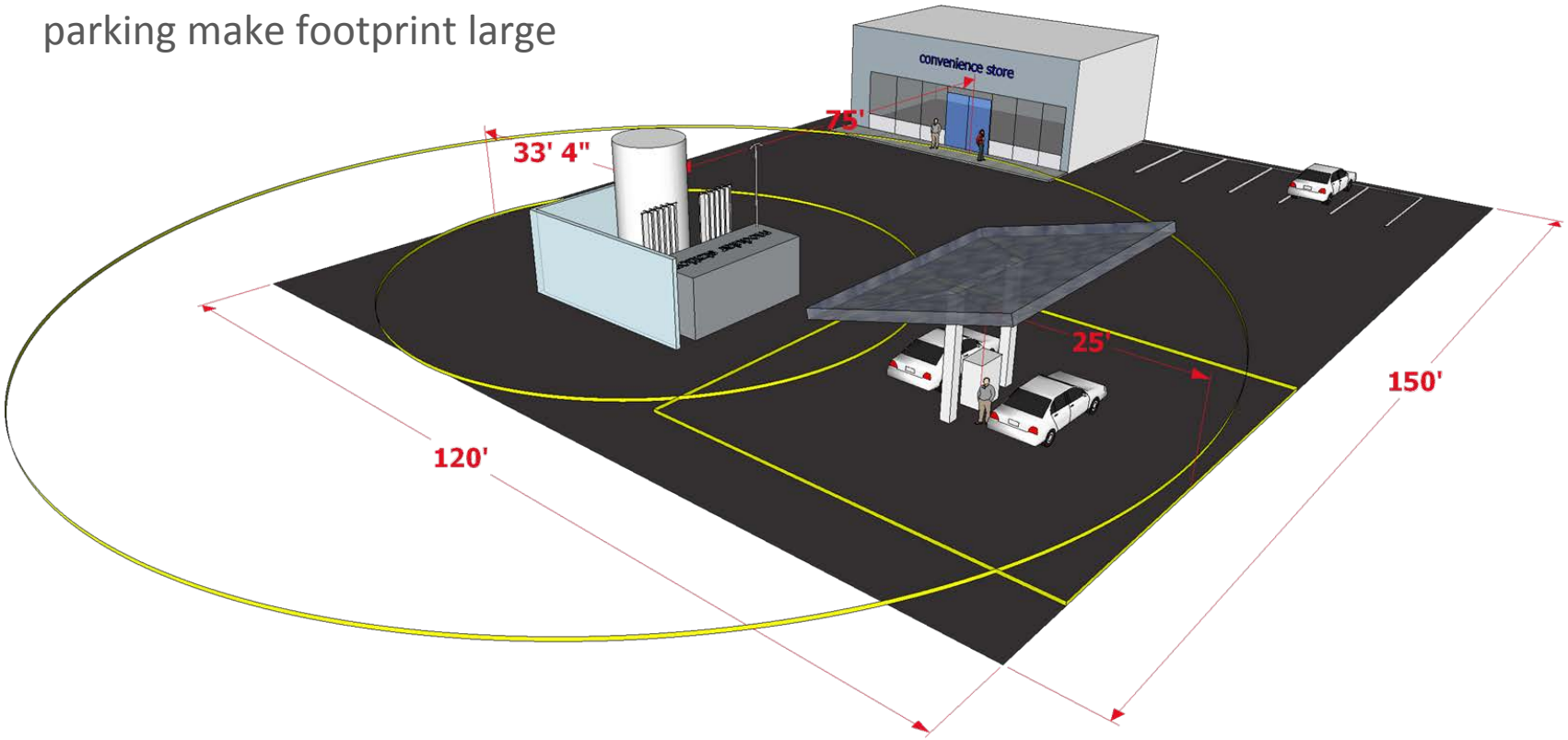
Experiment and simulation of indoor H2 releases

Laboratory-scale characterization of LH2 plumes and jets



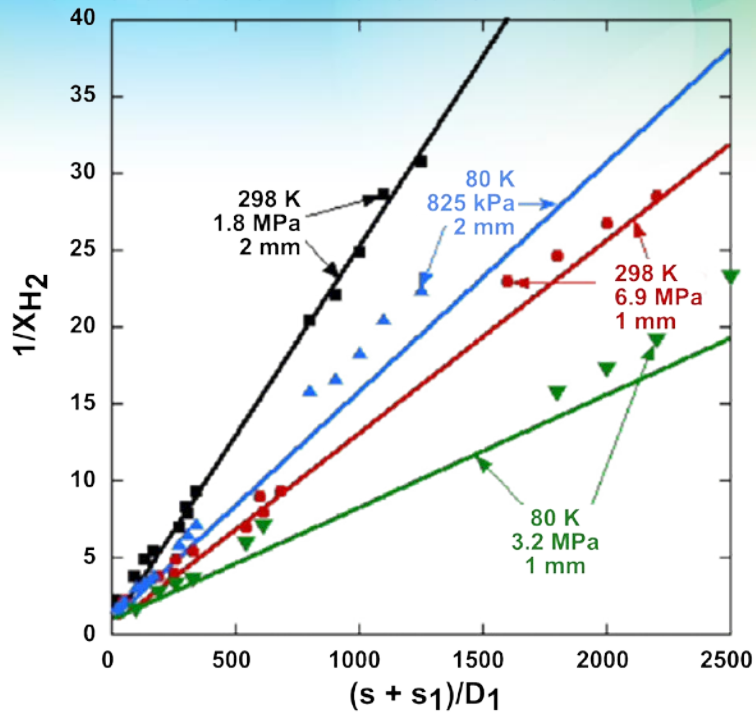
Current Focus Area: Separation distances for bulk liquefied hydrogen are based on consensus, not science

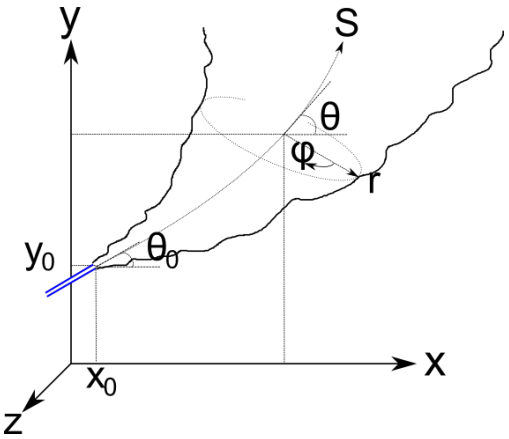
- Previous work by this group led to science-based, reduced, gaseous H_2 separation distances
- Higher energy density of liquid hydrogen over compressed H_2 makes it more economically favorable for larger fueling stations
- Even with credits for fire-rated barrier wall, 75 ft. offset to building intakes and parking make footprint large

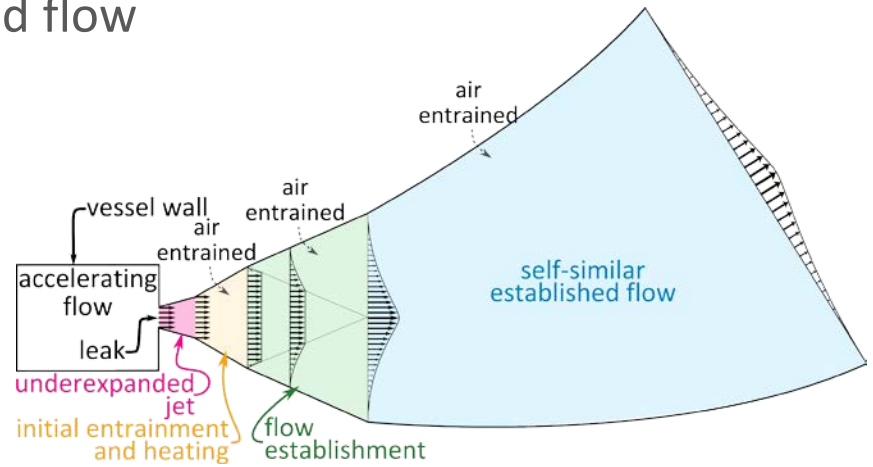


Our conceptual model for LH2 releases needs further validation

- Conservation of mass, momentum, species, energy
- 5-zones:
  - Zone 0: accelerating flow
  - Zone 1: underexpanded jet
  - Zone 2: initial entrainment and heating
  - Zone 3: flow establishment
  - Zone 4: self-similar, established flow

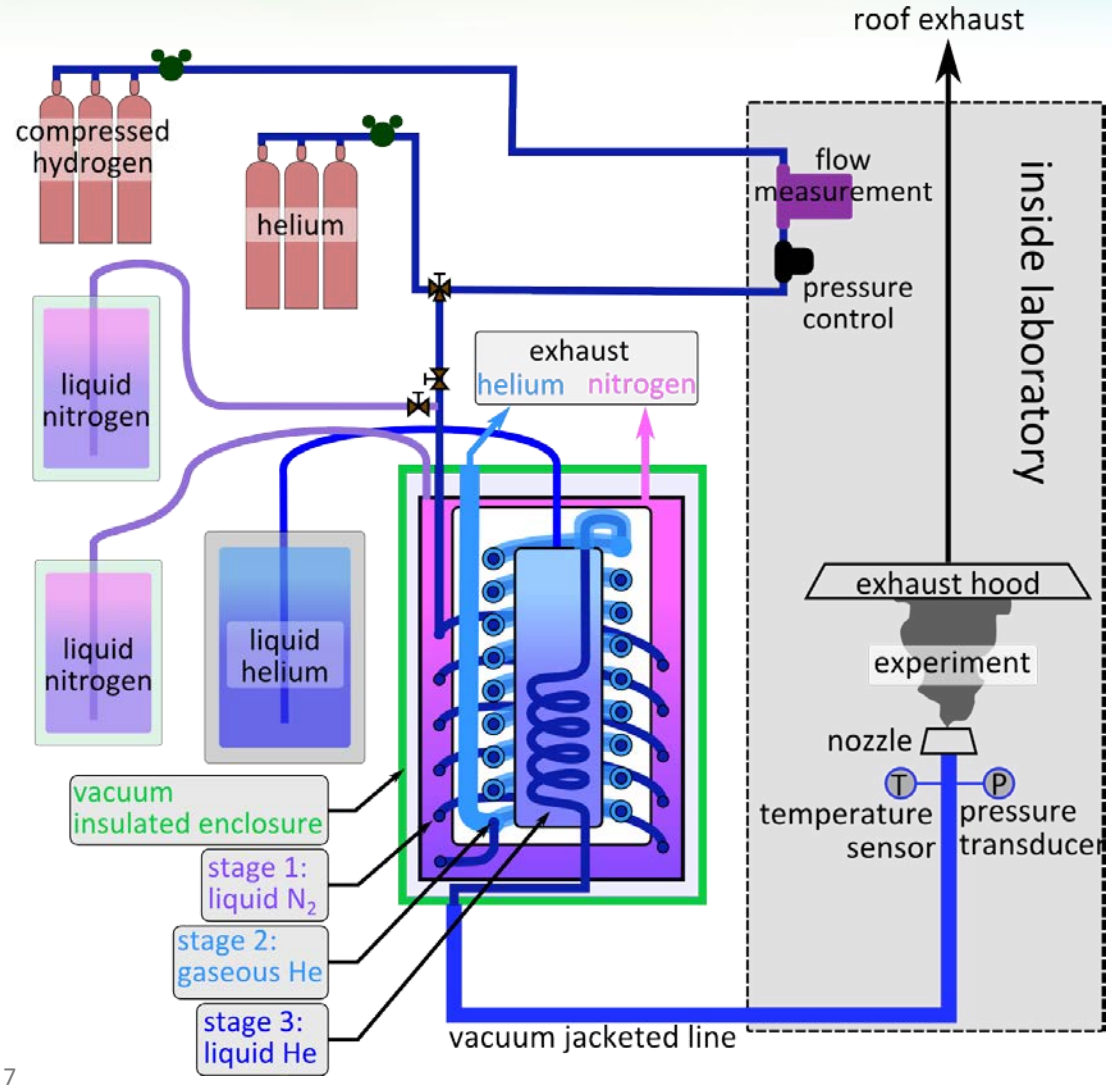


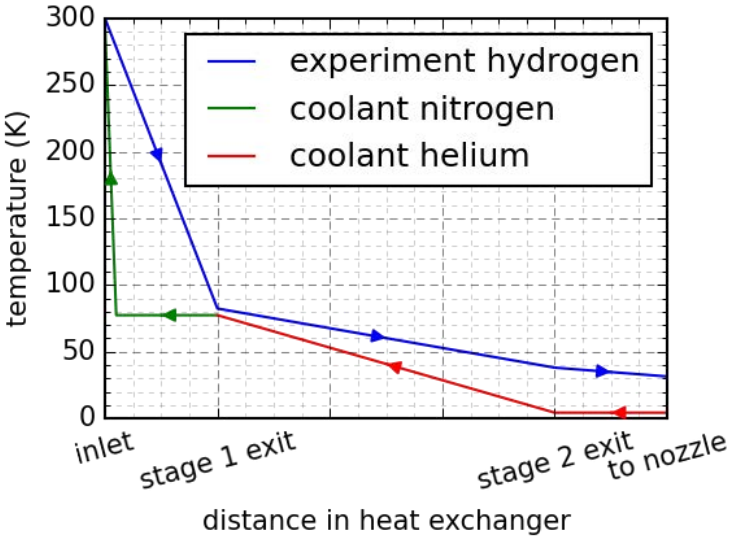




Houf & Winters, IJHE, 2013

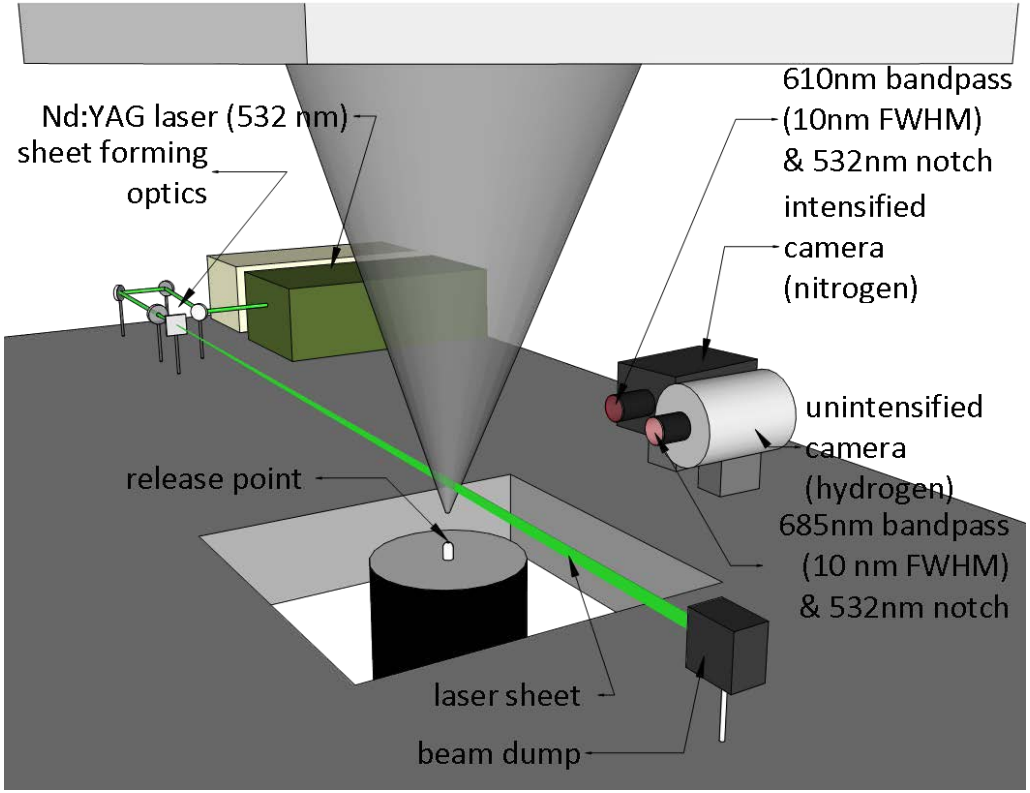
Experiments releasing ultra-cold hydrogen in the laboratory will help to validate the model





- Accurate control/measurement of boundary conditions

Developed and implemented Raman imaging technique to measure cryogenic plumes



- Filtered Rayleigh had insufficient Mie scattering light suppression (OD≈3)
- Raman scattering enables higher optical density filters
  - 10 nm FWHM bandpass filters at wavelengths of interest
  - OD of 12 @ all wavelengths
  - OD of 18 @ 532 nm
- Enables simultaneous measurement of concentration and temperature

Remaining challenges: Phenomena from large-scale releases are not well understood

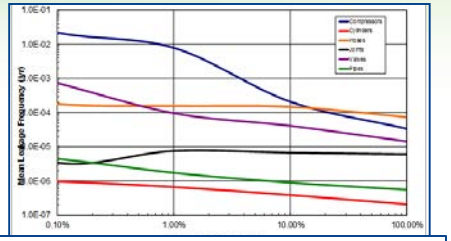
Need experiments to characterize:

- Pooling
- Evaporation from LH2 pools

Planning underway for experiments at Sandia (Albuquerque) facilities:

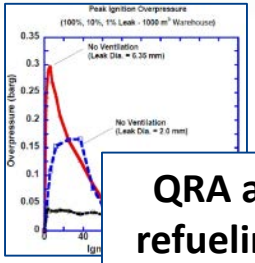
- Thermal test complex
  - Flame cell
    - Up to 3m diameter pool
    - 18.3 m dia. x 12.2 m high
    - Well characterized conditions for model validation
  - Crosswind test facility
    - Dispersion in controlled crosswind
    - Single-direction flow
    - Well-characterized ambient conditions
- Severe Accident Phenomena/Analysis (Surtsey)
  - 100 m^3 pressure vessel with 6 levels of instrumentation ports

Quantitative Risk Assessment is enabling infrastructure



Established risk-informed processes for separation distances

PLL	5.084e-04
FAR	0.1161
AIR	2.322e-06



QRA applied to indoor refueling to inform code revision

Performance-based system layout demonstrated

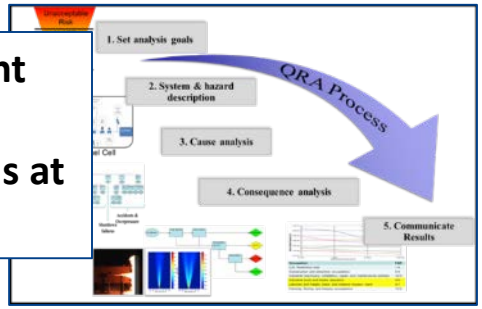
ISO TC197 WG24 incorporating QRA and behavior modeling

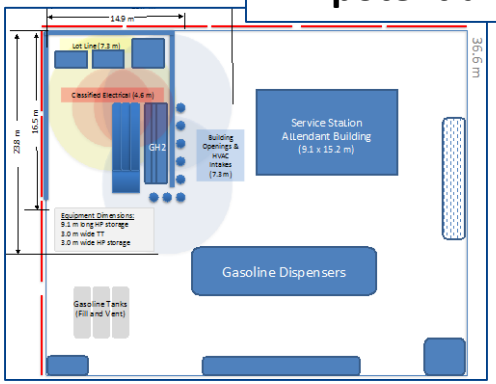
2005 2007 2009 2011 2013 2015 2017

QRA-informed separation distances in NFPA 2

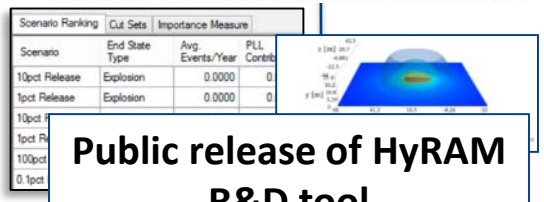
20% station penetration potential due to QRA

Risk assessment proposed for hydrogen systems at ICHS



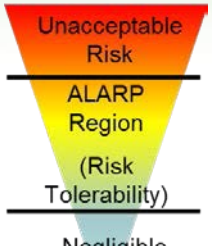


HyRAM HYDROGEN RISK ASSESSMENT MODELS

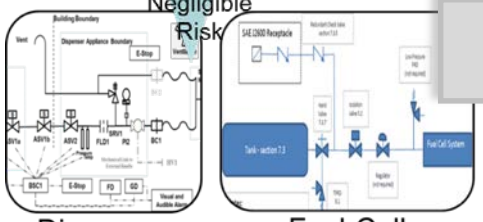


Public release of HyRAM R&D tool

The art and science of Quantitative Risk Assessment



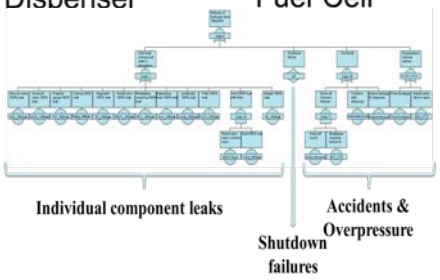
1. Set analysis goals



2. System & hazard description

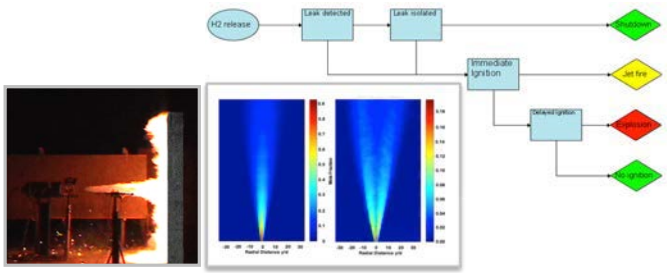
User-specific – Each analyst can establish own analysis goals, defines own system

3. Cause analysis



User-neutral – All analysts apply established science & engineering basis (encoded in HyRAM)

4. Consequence analysis



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

5. Communicate Results

HyRAM: Making hydrogen safety science accessible through integrated tools

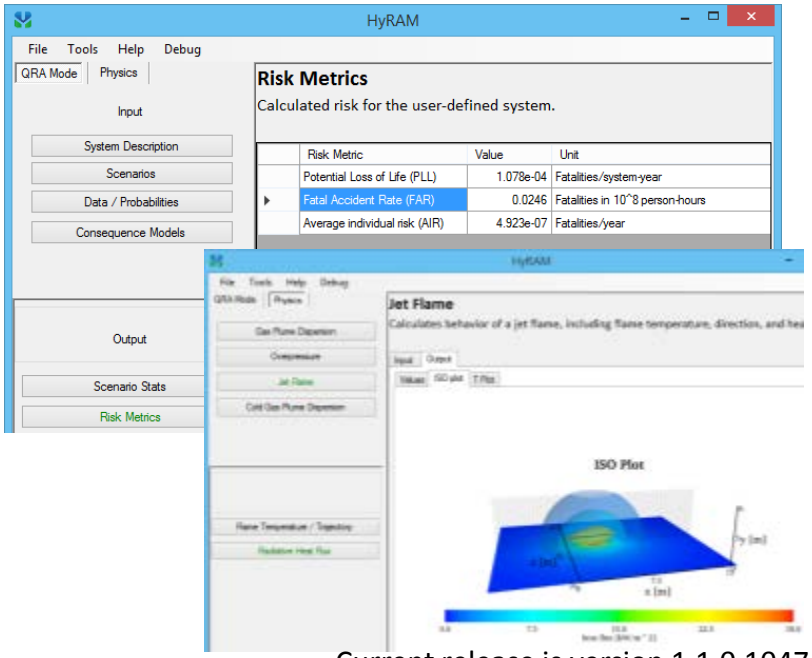
First-of-its-kind integration platform for state-of-the-art hydrogen safety models & data - **built to put the R&D into the hands of industry safety experts**

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

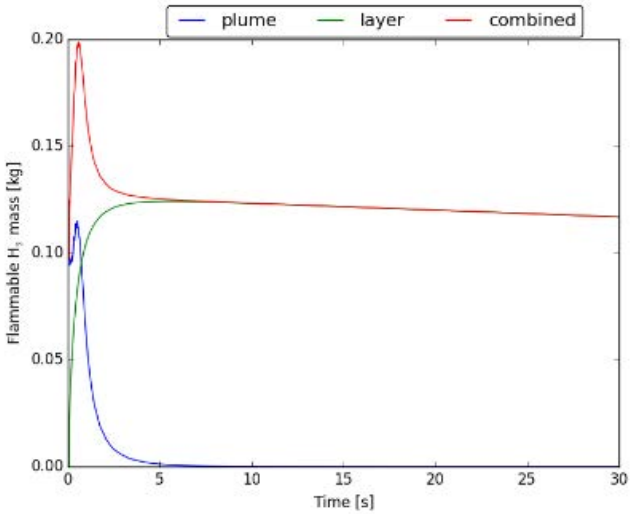


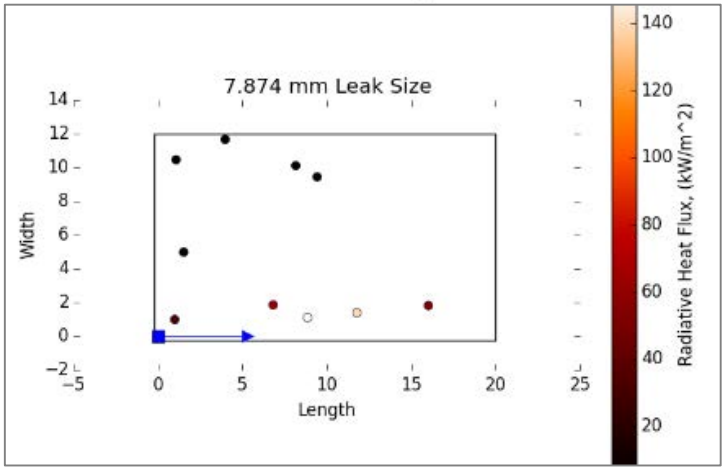
Current release is version 1.1.0.1047

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

Status: HyRAM 1.1 released Feb 2017

- The new version **achieves 67% reduction in curved flame computing time**, QRA mode now runs in ~3 min (vs. 8 min)
- **New features in HyRAM 1.1:**
  - **Makes internal FY16 models public:** Overpressure, layer, gas plume models & Engineering Toolkit (ETK)
  - **Curved flame module now in QRA mode:** Improved physical accuracy; shorter hazard distances
  - **Reconfigured occupant positions to be in 3D** – no longer restricts exposures to ground level (e.g., relevant for H2FIRST rooftop scenarios; maritime work).
  - **New GUIs in QRA mode** – outputs occupant position, heat flux on lot footprint.
  - **New TNT Equivalent model in Tool Kit**





Future work

- Behavior Characterization
  - Complete Raman imaging characterization of cryogenic hydrogen releases
  - Validate/modify ColdPLUME model
  - Develop and conduct safety and test plans for large-scale and enclosure/accumulation experiments
  - Simulate scenarios driving separation distances in NFPA 2/55
- HyRAM
  - Integrate validated ColdPLUME model into HyRAM release
  - Develop GUIS and source code for ColdPLUME model
  - Establish a process to enable external R&D community to contribute models and data, i.e. as plug-ins
- QRA for Materials
  - Commence research plan to characterize and calculate risk associated with material failures in H2 infrastructure gap

Summary

- Quantitative risk assessment provides opportunity to accelerate development of and add rigor to Codes & Standards
- Bring scientific rigor into decision-making for code revisions by addressing the lack of safety data and technical information
  - Develop scientific models to accurately predict hazards and harm from hydrogen releases and flames
  - Generate validation data for behavior models where it is lacking
- Code developers (e.g., NFPA, ISO) require increasingly rigorous and defensible technical basis for codes
- Main uses of QRA within Codes & Standards:
  - Create a risk-informed requirement (e.g., QRA, models for safety distances)
  - Allow risk-equivalent code compliance (e.g., performance-based design),
  - Develop risk-based codes & regulation (e.g., Dutch RIVM approach to regulation)

Technical Back-Up Slides

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

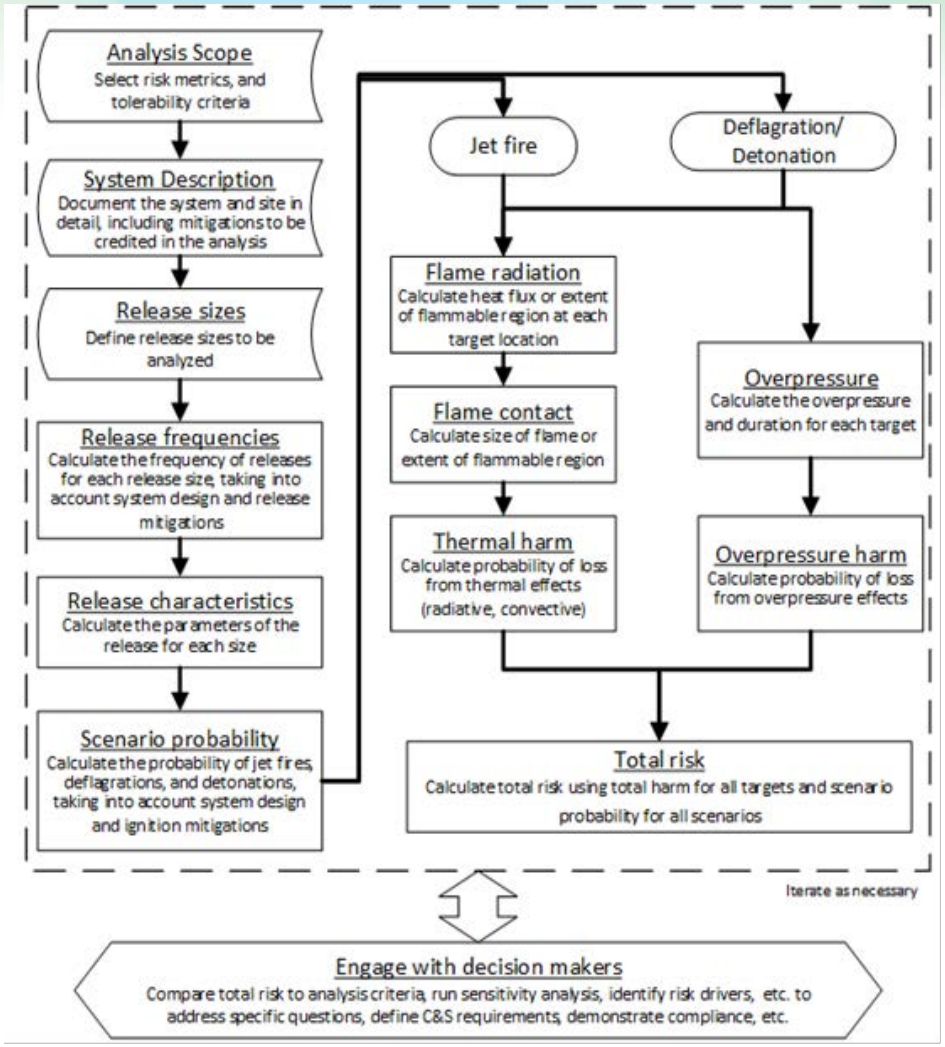
- Properties of Hydrogen
- Unignited releases: Orifice flow; Notional nozzles; Gas jet/plume; Accumulation in enclosures
- Ignited releases: Jet flames w/ and w/o buoyancy; overpressures in enclosures

Mathematics Middleware

- Unit Conversion System
- Math.NET Numerics

Documentation

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

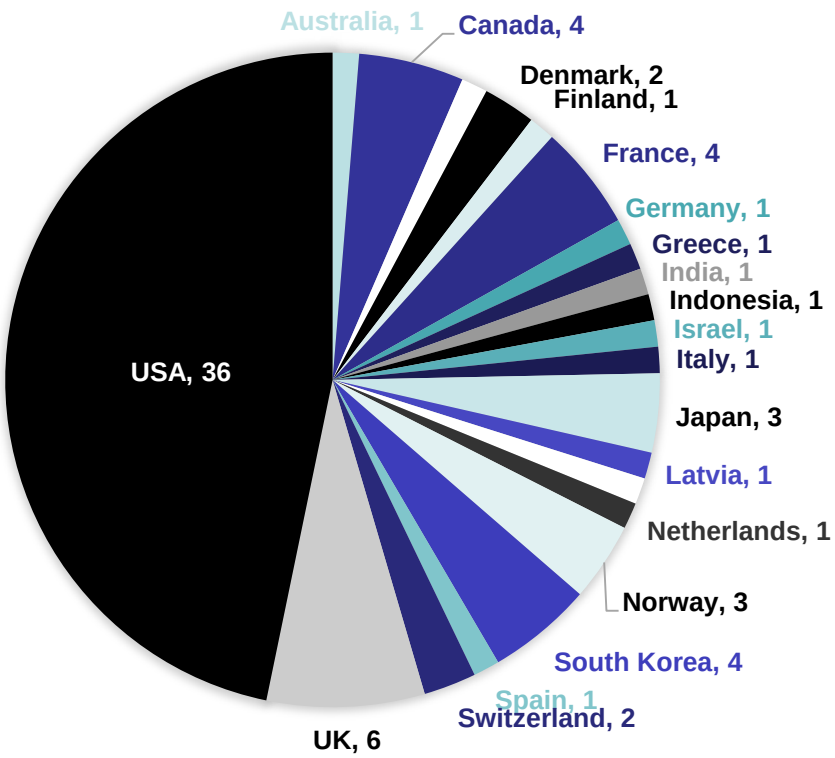


+ Free download via web

HyRAM users span stakeholder groups, applications, countries

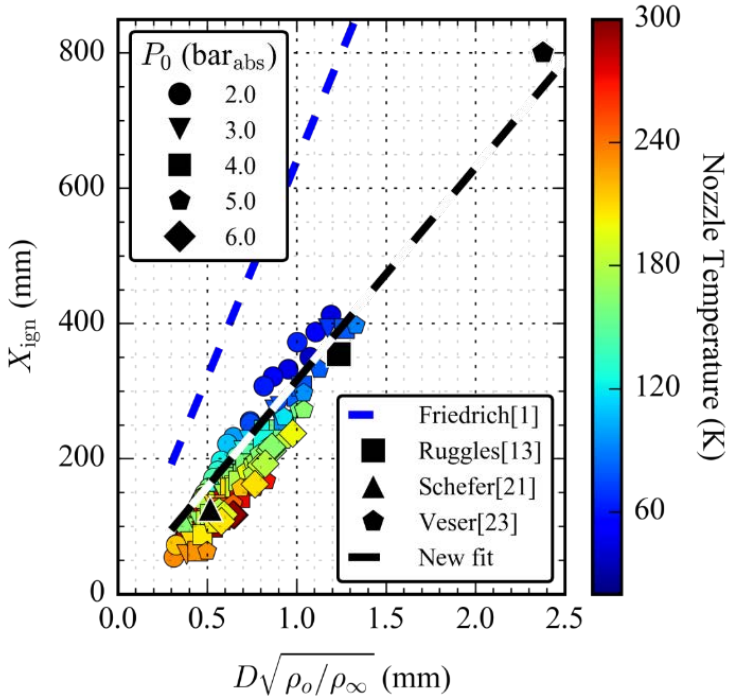
- 77 active users
- 137 unique downloads

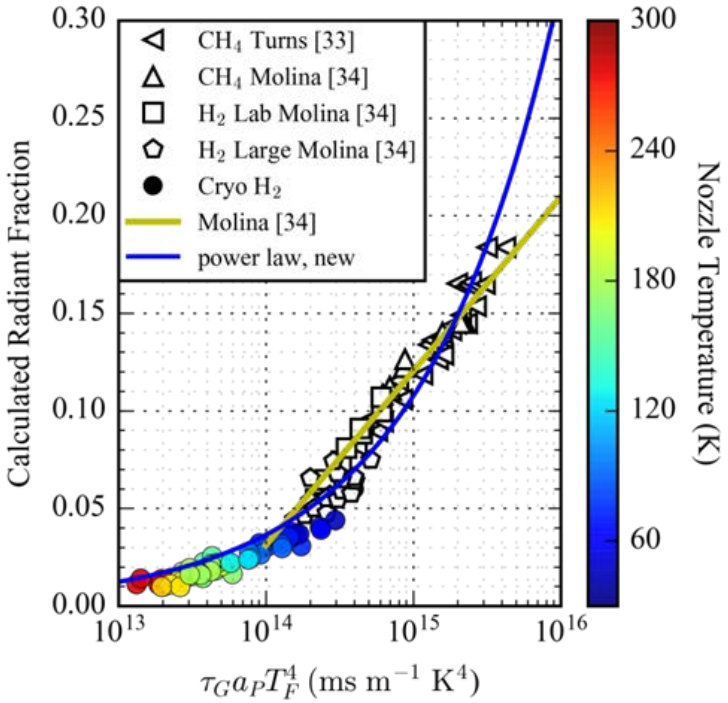
Users by Country



- Active users include:
  - **US labs & regulators**: SNL, NREL, PNNL, NASA; Hawaii Natural Energy Institute
  - **Gas suppliers**: Air Liquide, Linde, Shell, Indian Oil
  - **Universities**: UQTR (CA), UNAM (Mx), Yokohama National Uni (JP), Washington State Univ., Sheffield (UK) Ulster (UK), DTU (DK), Chung-Ang Uni. (KOR), HU (KOR), UHM, HSN (NO),
  - **Int'l labs & regulators**: PSI (CH), NMRI (JP), KGS (Korea Gas Safety); RIVM (NL - Centre for Environmental Safety & Security), Bureau Veritas Marine (FR); IPMO, VTT (FIN)
  - **Manufacturers**: H2Logic; Plug Power, Inc.; PowerTech Labs; Kawasaki Heavy Industries, Michelin,
  - **Consulting**: Arcola Energy, AVT, CNL, Zero Carbon Energy Solutions, Witte Engineered Gases; FonCSI; Lilleaker Consulting AS; HNTB Corporation; Jacobs Technology; IntelliSIMS, Fp2Fire, Neodyme; The IET

Ignition distance and radiant fraction were mapped out FY16

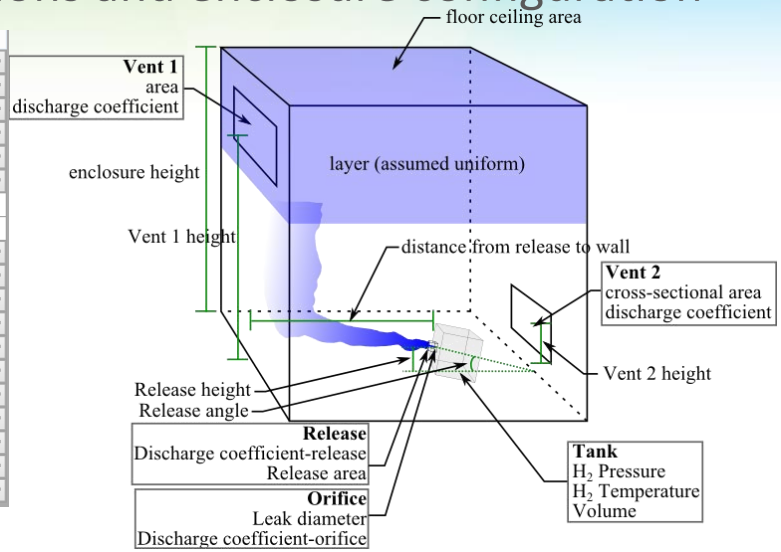




Overpressure & layer modules

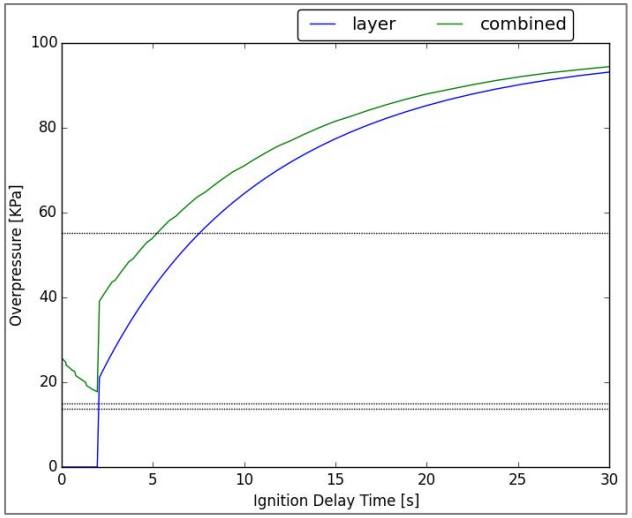
Input: Release conditions and enclosure configuration

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)

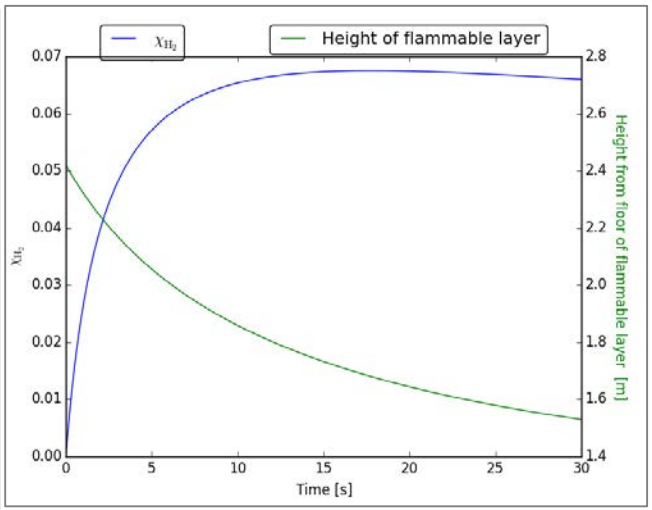


Maximum pressure (Pa): 94418.2835711473

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

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



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

- **Usage in current RCS and FCTO activities**
  - **NFPA 2:** LH_2 separation distances, revision of GH_2 separation distances
  - **ISO CD-19880-1:** Support ISO as it develops DIS from the CD
  - **New in FY17 H2FIRST:** HyRAM being used to support comparison of reference stations; risk-informed comparison of on site storage (rooftop vs. underground vs. at grade)
- **Successful application of SNL models & approach in H_2 RCS:**
  - **Completed in FY17: ISO CD-19880-1 Annex A**: Developed regional safety distance examples using SNL's HyRAM tool
  - **Completed in FY17: ISO CD-19880-1 Ch. 5:** Developed consensus approach for defining specific mitigations using regional criteria
  - **NFPA2 Ch. 5, 7, 10**: Enabling *Performance-based* compliance option (SAND2015-4500); Established GH_2 separation distances (SAND2012-10150); Calculated risk from indoor fueling (SAND2012-10150)
- **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 for components (e.g., pressure vessels, compressors)