Sandia National Laboratories

H2FC Hydrogen and Fuel Cells Program

Hydrogen Quantitative Risk Assessment

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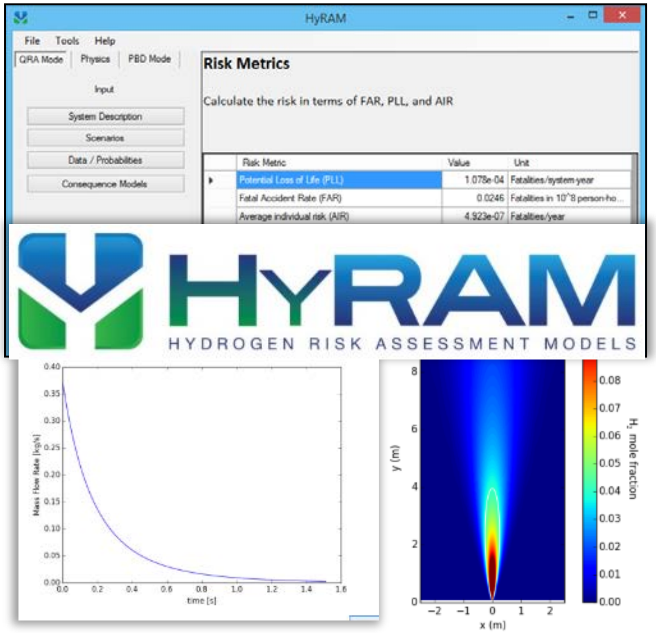

2017 DOE Hydrogen and Fuel Cells Annual Merit Review
June 6, 2017

Project # SCS011

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Overview

Timeline

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

  * 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

Budget

- FY16 DOE Funding: $370k
- Planned FY17 DOE Funding: $325k

Partners

Industry & research collaborators:
Linde, Gexcon, PNNL, NREL, 40+ organizations using HyRAM

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

International engagement:
HySafe, IEA HIA Task 37

Relevance

Objective: Develop a rigorous **scientific & engineering basis** for assessing safety risk of H_2 systems and **facilitate use of that information** for revising RCS for emerging hydrogen technologies.

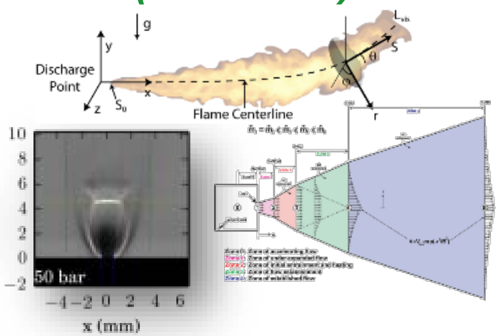
Barrier from 2013 SCS MYRDD	SNL Goal
A. Safety Data and Information: Limited Access and Availability	Build validated H2 behavior physics models that enable industry-led C&S revision and Quantitative Risk Assessment.
F. Enabling national and international markets requires consistent RCS	Develop H_2-specific QRA [Quantitative Risk Assessment] tools & methods which support SCS decisions and
G. Insufficient technical data to revise standards	Create analyses and data products that enable SCS and safety analyses to be based on a strong science & engineering basis.

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)

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

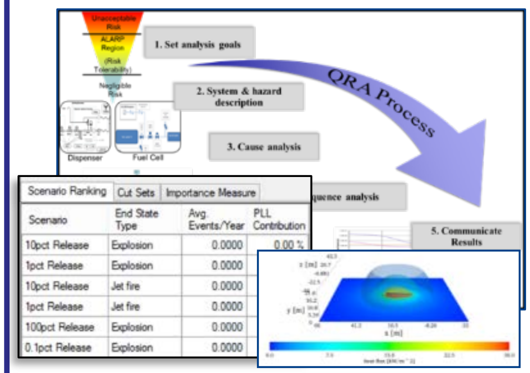
Behavior R&D (SCS 010)



Develop and validate scientific models

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

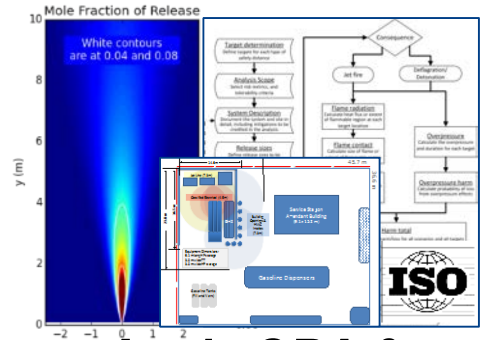
Risk R&D (SCS 011)



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

HYRAM
HYDROGEN RISK ASSESSMENT MODELS

Approach / FY16-17 Milestones

	Completion date or status
Essential maintenance & reporting on HyRAM	
• Licensing, distribution, bug reporting, bug fixes, testing • Quality review: Full walkthrough of HyRAM scientific source code • Critical stabilization & bug fixes on scientific modules, and stability on multiple computer platforms • Develop & integrate TNT equivalent module; release • HyRAM 1.1 public release containing all modules developed in 2016	Ongoing / as needed August 2016 In HyRAM 1.1 In HyRAM 1.1 February 2017
HyRAM dissemination & documentation	
• HyRAM 1.0 overview DOE webinar • Publish technical reference report on HyRAM V1.1 algorithms • Engage with stakeholders, including HySafe, IEA HIA Task 37, NPFA 2, ISO • HySafe research priorities workshop	Apr. 26, 2016 Mar 2017 Ongoing / as needed Sept 2016
Evaluate feasibility of using QRA, materials info for H2 storage technologies	
• Literature review, gap study & survey questions • Report on state-of-the-art and R&D needs	On track for May 2017 On track for Sept 2017

HyRAM: Making hydrogen safety science accessible through integrated tools

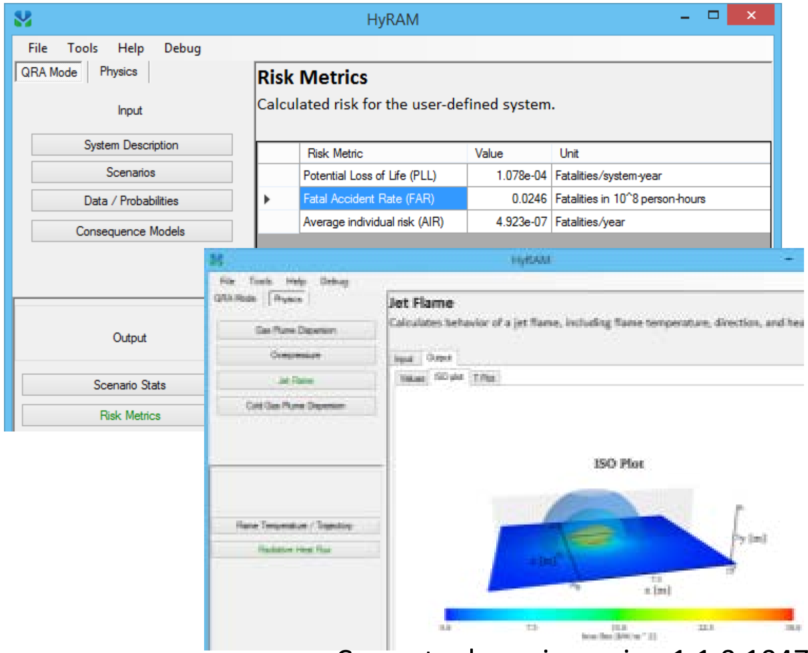
First-of-its-kind integration platform for state-of-the-art hydrogen safety models & data - **built to put the R&D into the hands of industry safety experts**

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

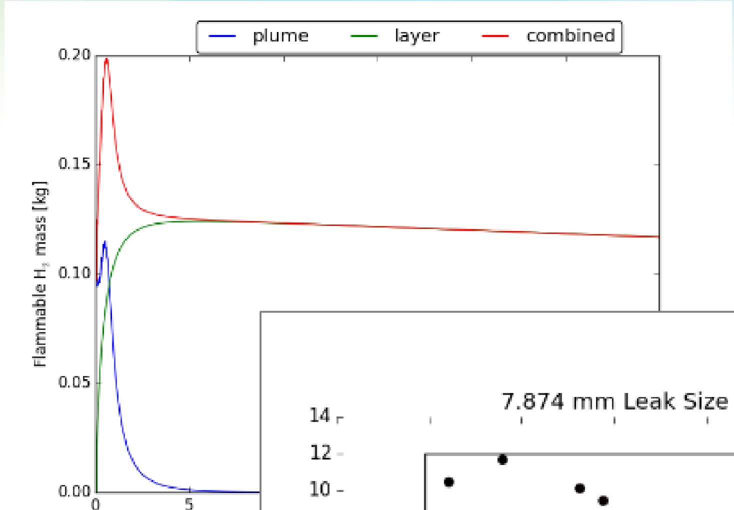
Available at http://hyram.sandia.gov

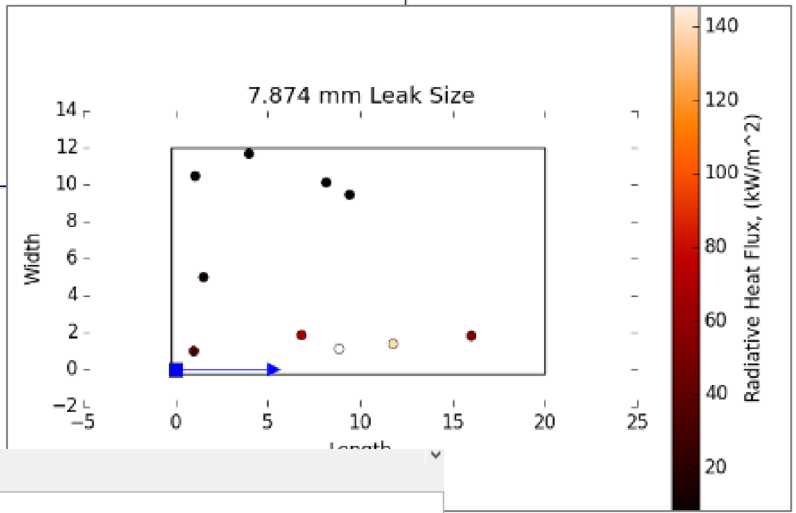
Accomplishment: HyRAM 1.1 released Feb 2017; new features

- **Makes internal FY16 models public:** Overpressure, layer, gas plume models & Engineering Toolkit (ETK)
- **Curved flame module now in QRA mode; removed straight flame model –** 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 ETK**

New models enable new insights in usability. For example, H2FIRST Urban sites task (e.g.- siting for rooftop/canopy storage) and enclosures.

Accomplishment: HyRAM 1.1 released Feb 2017; major improvements





- The new version **achieves 67% reduction in curved flame computing time**, QRA mode now runs in ~2.5min (vs. 7.75min)
- **Reflects important software quality activities (see next slide)**

Components | System Parameters | Facility Parameters | Boundary Conditions

Facility | Occupants

	Number of Targets	Description	X Loc. Dist. Type	X Loc. Dist. Param. A	X Loc. Dist. Param. B	Y Loc. Dist. Type	Y Loc. Dist. Param. A	Y Loc. Dist. Param. B	Z Loc. Dist. Type	Z Loc. Dist. Param. A	Z Loc. Dist. Param. B	Unit
	1	Hugger	Deterministic	1		Determi...	1	0	Deter...	1		Meter
▸	9	Station workers	Uniform	1	20	Determi...	1	0	Uniform	1	12	Meter
*												

HyRAM *reduces industry burden* - allows industry to focus on getting safety insights rather than creating, validating, and documenting algorithms.

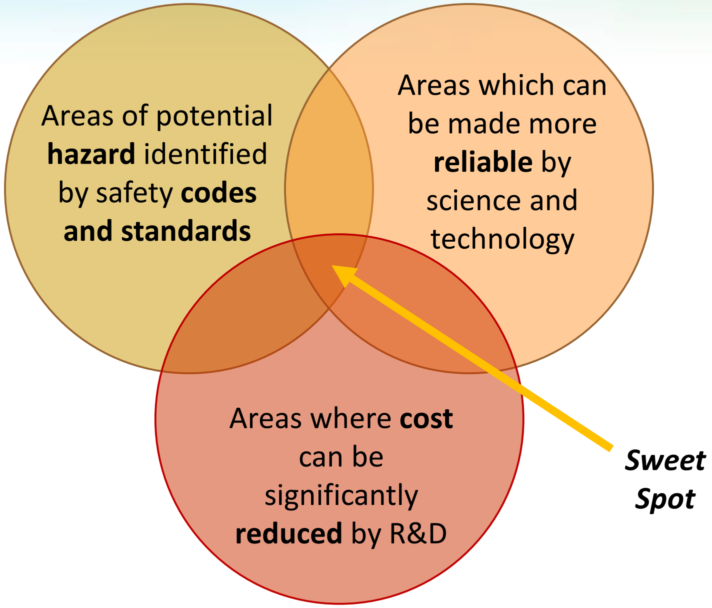
Accomplishment: HyRAM quality review, testing, maintenance

- Significant quality assurance efforts underlie HyRAM 1.1
  - Line-by-line walkthrough of HyRAM scientific source code
    - Identified two scientific bugs in internal versions – corrected in HyRAM 1.1
    - Identified errors in algorithm report – corrected in HyRAM 1.1
    - Removed duplicated functionality between QRA mode and physics mode – significantly reduces chances for introducing future defects
- Critical bug fixes
  - Internationalization issue: Comma vs. decimal
  - Compatibility with multiple versions of Windows (7, 8, 8.1, 10; US & int'l)
  - Numerous fixes to stability; compatibility with Python;

- **Quality assurance efforts are essential for user confidence, usability.**
- **Important step in transitioning SNL technologies, R&D to H2 industry**

Progress: Identification of gaps in Hydrogen storage technologies

- **Long-term goal: Leverage foundational R&D capabilities in QRA and materials** to characterize and calculate risk associated with a key H_2 infrastructure gap (storage) - **support safety, reduce barriers with near-to-mid-term impact on RCS**
- **Using QRA R&D to enhance reliability and reduce costs** for H2 technologies
  - Reviewed literature on known R&D gaps - Exploring state-of-the-art risk methods which incorporate concepts from materials, scientific computing, and data analytics.
  - Designing semi-structured interview protocol to engage with industry; Motivates industry buy-in and participation early in the R&D



- Potential impact on multiple FCTO program elements: Safety Codes and Standards, Delivery, and Storage
- Leveraging SNL H2 program core capabilities (risk, materials), and other SNL programs (scientific computing) to address critical barriers for industry

Accomplishment: Research dissemination & documentation (April '16-Mar '17)

- **HyRAM 1.1 released February 2017** – available at http://hyram.sandia.gov
- **Technical reference manual for HyRAM 1.1 released March 2017**.
  - KM Groth, ES Hecht , JT Reynolds, ML Blaylock, EE Carrier. *Methodology for assessing the safety of Hydrogen Systems: HyRAM 1.1 technical reference manual.* SAND2017-2998.
- **Started HyRAM Forum on H2Tools.org** for users to exchange information, ask questions, provide feedback
- Substantial engagement with external technical community
  - HySAFE research priorities workshop Sept 2016
  - IEA HIA Task 37: leadership of sub-team on risk integration toolkits
  - 4 journal papers, 9 presentations, including 2 invited talks at universities, 2 invited talks at conferences, DOE webinar

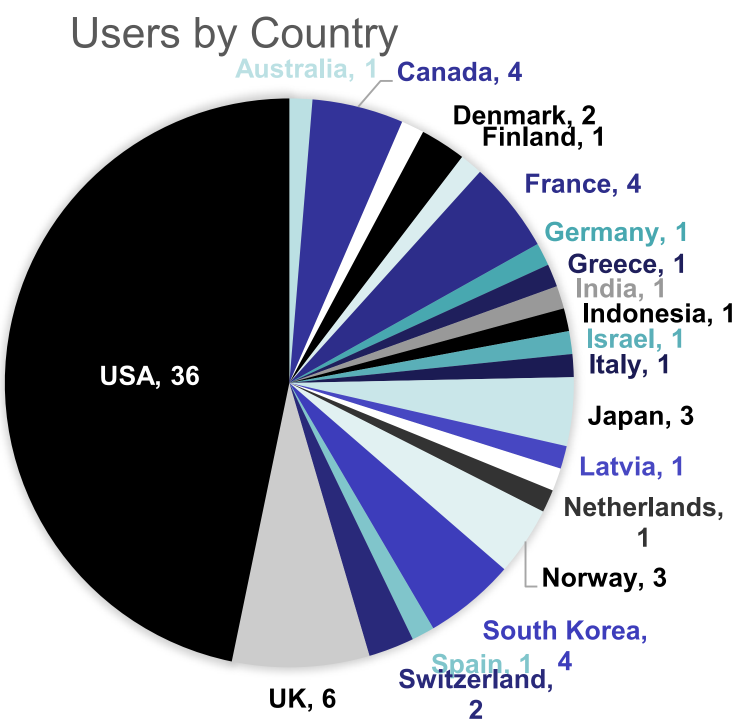
***Communication reduces stakeholder burden* – we are reaching out to them; tailoring communication materials to multiple audiences, platforms**

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 A “Safety Integration Toolkits”
- **H2USA -** Various working groups
- **CaFCP Auto OEM group; NFPA FPRF -** CRADA to support research on LH2 releases, QRA, and PBD

Collaborations & Tech Transfer: HyRAM active users span stakeholder groups, applications, countries

- 77 active users who have obtained license keys
- 137 unique downloads



- 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

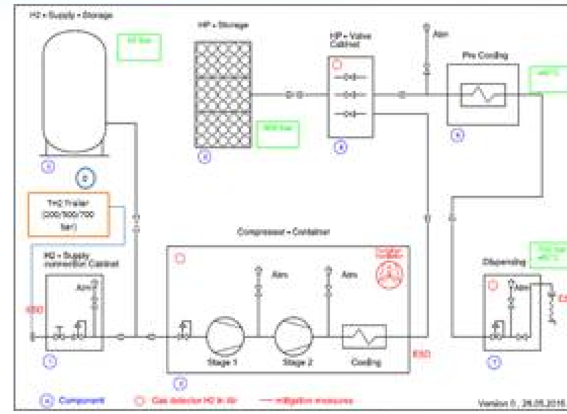
Tech Transfer

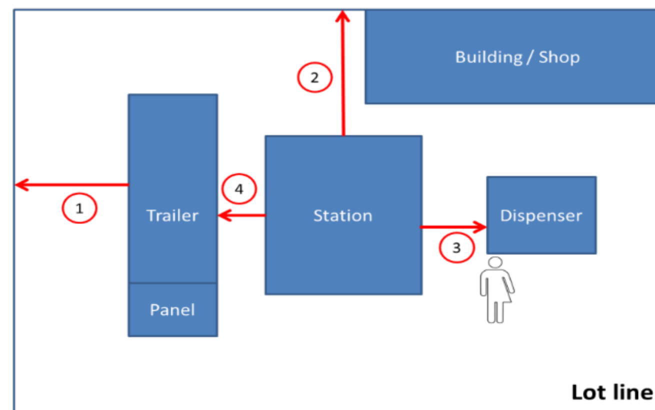
- Substantial engagement with external technical community
  - HySAFE research priorities workshop Sept 2016
  - IEA HIA Task 37: leadership of sub-team on risk integration toolkits
  - 4 journal papers, 9 presentations, including 2 invited talks at universities, 2 invited talks at conferences, DOE webinar
- HyRAM 1.1 is available from HyRAM website.
- Hosted 4 student interns:
  - UIUC, in last year of PhD in CS
  - NM Tech, junior in CS
  - 2 High School, 1 now at Texas A&M studying Mech Eng.

Impact: QRA R&D enabled development of codes & standards in FY16/17

- **ISO CD-19880-1** (Went to vote in Nov 2016)
  - Sub-team co-lead by SNL and Air Liquide wrote Chapter 5 (safety methodology and mitigations) based on SNL methodology
  - HyRAM used to develop all safety distances in ISO CD-19880-1 Annex A
  - HyRAM usability, speed combined with ISO methodology flexibility and transparency, documentation format as "***more beneficial to permitting than the resulting distances***" and a *"key reason for coming to consensus"*
- **H2FIRST project**
  - HyRAM being used to calculate the Baseline Risk Values for the 300 kg/day Reference Station Design
- **NFPA 2** – (In revision for 2020 Edition)
  - HyRAM used to revise bulk gaseous hydrogen separation distances; models being developed to enable revision of liquid separation distances using same methodology

ISO Risk Analysis





See SCS025 for additional detail

- **HyRAM enabled major progress toward harmonization of safety distance methodology used in ISO & NFPA 2**
- **Risk-informed code requirements based on enable more sites to readily accept hydrogen infrastructure**

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 HyRAM 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**

- **Seeking external support and partners for HyRAM maturation;** to lead or support formal software activities, validation, testing, training, etc.

Proposed future work

- Rest of FY17:
  - QRA R&D for storage: **Support safety, reduce barriers with near-to-mid-term impact on RCS**
    - Write up literature survey / gap analysis
    - Survey experts from industry on RCS gaps, cost drivers
    - **Deliver a plan to** characterize and calculate risk associated with a key H2 infrastructure gap (storage) HyRAM
  - HyRAM
    - Continue to support distribution of HyRAM 1.1
    - Fix critical user-reported software defects
- FY18:
  - Storage R&D: apply risk methodologies to H_2 storage materials
  - HyRAM
    - Develop GUIs & source code for cold-plume model based on experimental results (from SCS010)
    - Establish a process to enable external R&D community to contribute models and data, i.e. as plug-ins
    - Explore extensions to enable HyRAM to support design optimization

Response to last year's Reviewer's comments

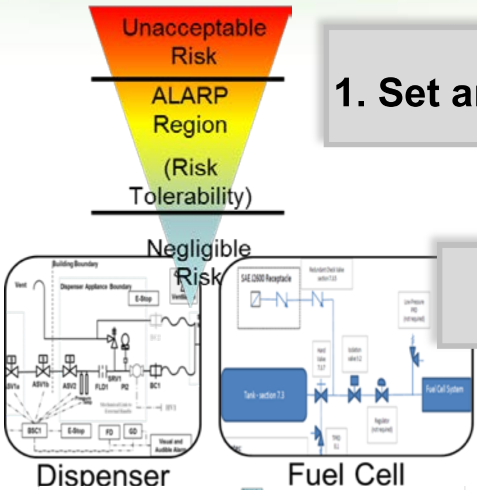
- *<u>AMR2016 comment:</u> The project needs more emphasis on adding liquid hydrogen capability.*
  - We will begin incorporating models for cryogenic hydrogen releases into HyRAM once the validation experiments in SCS010 have been completed. We anticipate this will occur in FY18.
- *<u>AMR2016 comment:</u> There may be additional recommendations from users as they begin to work with HyRAM, which may result in the need for development of additional modules, further data, etc. It would be good if this project were to continue with sufficient time and funding to accommodate such feedback. (2 comments to this effect)*
  - There are many areas where additional modules and data could enhance the RCS and we are actively maintaining HyRAM as well as conducting focused R&D activities on key knowledge gaps. We are also looking for partners to continue maturation of HyRAM; please contact Sandia's technology transfer office if interested.
- *<u>AMR2016 comment:</u> While this model is focused on hydrogen fueling stations, it would be great to develop a tool (whether additional modules or a new modeling tool) that could help answer questions posed by regulators, such as what would happen if a hydrogen vehicle tank ruptured inside a parking garage, tunnel, etc.*
  - We are beginning to explore these possibilities with the new FY17 activity on QRA R&D for storage technologies.

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 V1.1 public release, Quality assurance; HyRAM speed-up, New GUIs, public features; Significant communication, publication, and tech transfer efforts; HyRAM enabled harmonization of safety distances in ISO CD-19980-1; Gap study on R&D, RCS needs for storage
- **Future Work**: Add cold H2 model; gap study for storage R&D; Targeted RCS engagement to reduce barriers

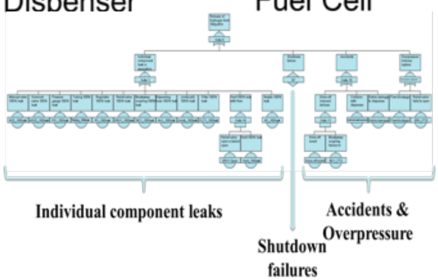
Technical Back-Up Slides

The art and science of QRA



1. Set analysis goals

2. System & hazard description

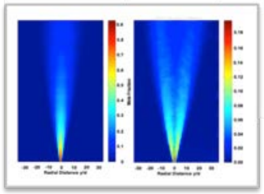


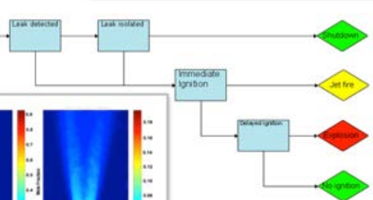
3. Cause analysis

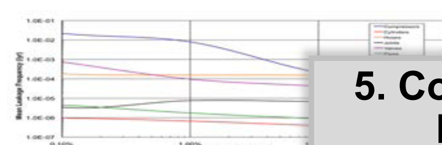
4. Consequence analysis

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

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







5. Communicate Results

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

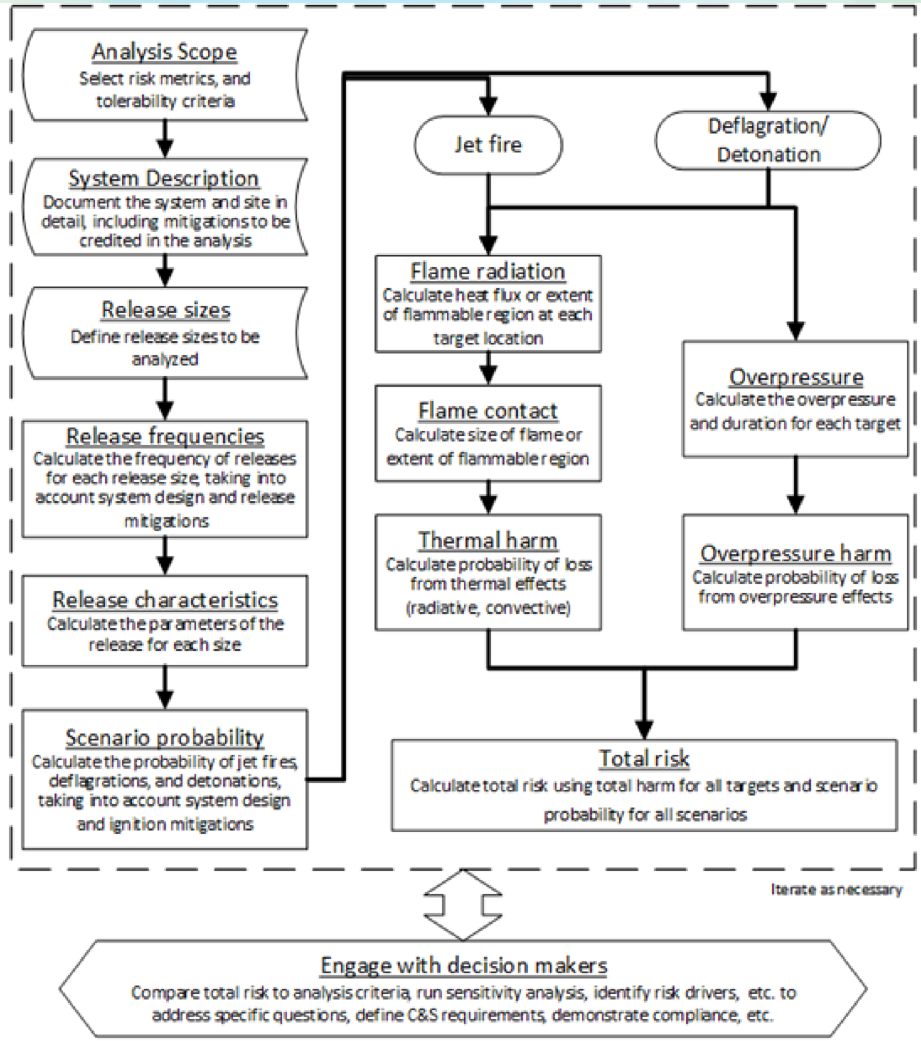
QRA Methodology
- Risk metrics calculations: FAR, PLL, AIR
- Scenario models & frequency
- Release frequency
- Harm models

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)

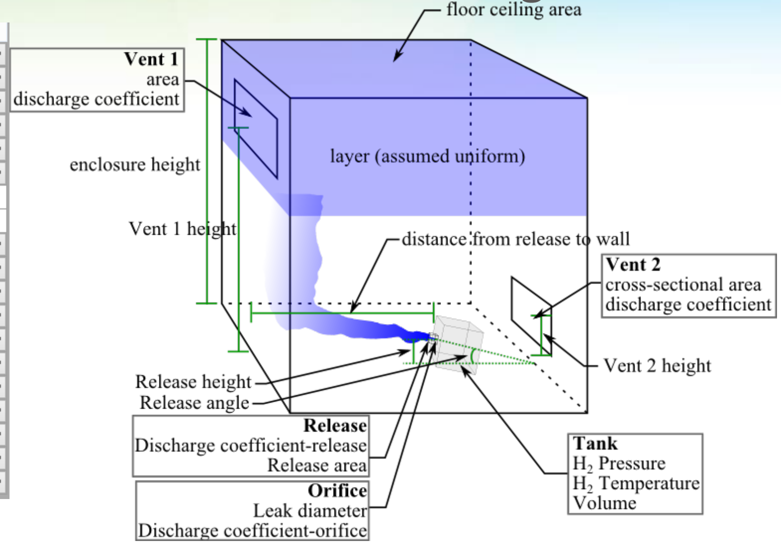


+ download via web

Overpressure & layer modules

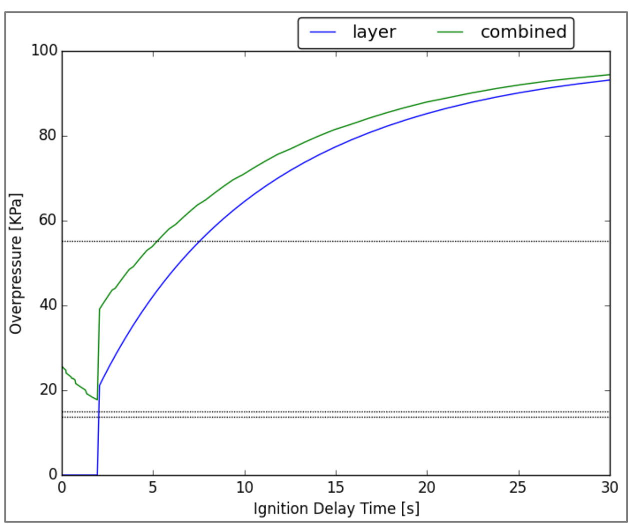
Input: Release conditions and enclosure configuration

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)

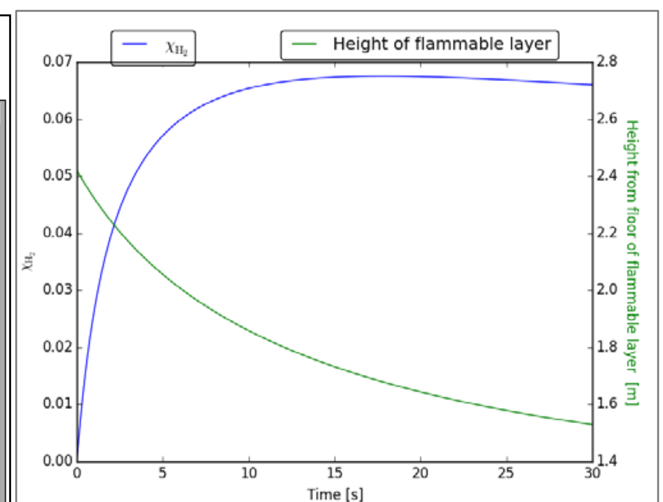


Maximum pressure (Pa): 94418.2835711473

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
16	[illegible]

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
[illegible]	[illegible]



Quantitative risk assessment (QRA) provides opportunity to accelerate development of & add rigor to RCS

- Code developers (e.g., NFPA, ISO) requiring increasingly rigorous and defensible technical basis for codes
- Increasing use of QRA within RCS over the last decade:
  - SFPE guidance issued in **2006;** NFPA in **2007**: "*Guidance Document for Incorporating Risk Concepts into NFPA Codes and Standards*"
- 3 main uses of QRA within RCS:
  1. Create a risk-informed requirement (e.g., QRA, models for safety distances)
  2. Allow risk-equivalent code compliance (e.g., performance-based design),
  3. Develop risk-based codes & regulation (e.g., Dutch RIVM approach to regulation)

Research Gaps Identified in Recent Workshops

2014 HySafe Research Priorities Workshop Washington, D.C. on Nov. 10-11, 2014

- Quantitative Risk Assessment (QRA) Tools (23%)
  - Want user-friendly and industry focused QRA software tool
  - Second highest priority is guidance for using risk in decision making
- Reduced Model Tools (15%)
  - Effects of barrier walls on flame and overpressure behavior
  - Consolidation of research and tools
- Indoor (13%)
  - Behavior of cryo jets, improved understanding of H2 indoors
- Unintended Release-Liquid (11%)
- Unintended Release-Gas (8%)
- Storage (8%)
- Integration Platforms (7%)
- Hydrogen Safety Training (7%)
- Materials Compatibility/Sensors (7%)
- Applications (2%)

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- Data and Phenomenology
  - Measurements of fatigue properties and causes of fatigue (15 votes)
  - Database for properties structural materials in H2 (12 votes)
  - Influence of welds on H2 compatibility (11 votes)
  - Crack initiation (4 votes)
  - Structural materials qualification for P/T for portable power (4 votes)
- Technology Development
  - Better containment materials: high strength, low cost, long life (8 votes)
  - Better H2 compressors (5 votes)
  - Non-destructive testing (5 votes)
  - Life assessment and leak-before-break criteria (4 votes)
- Codes and Standards
  - Testing protocols for materials evaluation (10 votes)
  - Criteria for engineering acceptance (9 votes)
  - List of acceptable materials (5 votes)
  - Design requirements for portable power (4 votes)
  - No international standard for >35 MPa (4 votes)
  - Variation in C&S relating to production/distribution/dispensing (4 votes)