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

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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 H₂ 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
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

Ignition of under-expanded H₂ jets

Barrier walls for risk reduction

Ignition limits of turbulent H₂ flows

Experiment and simulation of indoor H₂ releases

Laboratory-scale characterization of LH₂ plumes and jets

Advanced laser diagnostics applied to turbulent H₂ combustion
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 H₂ separation distances
- Higher energy density of liquid hydrogen over compressed H₂ 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
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

QRA applied to indoor refueling to inform code revision

ISO TC197 WG24 incorporating QRA and behavior modeling


Risk assessment proposed for hydrogen systems at ICHS

QRA-informed separation distances in NFPA 2

20% station penetration potential due to QRA

Public release of HyRAM R&D tool
The art and science of Quantitative Risk Assessment

1. Set analysis goals

2. System & hazard description

3. Cause analysis

4. Consequence analysis

5. Communicate Results

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

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

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

**Output:** Overpressure (ignited) & Height of accumulated layer (unignited)
Relevance: Bringing scientific rigor, into decision-making for SCS

- **Usage in current RCS and FCTO activities**
  - **NFPA 2**: LH₂ separation distances, revision of GH₂ 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 H₂ 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 GH₂ 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)