

An integrated toolkit for hydrogen infrastructure risk assessment

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Probabilistic Safety Assessment and Management (PSAM 12)

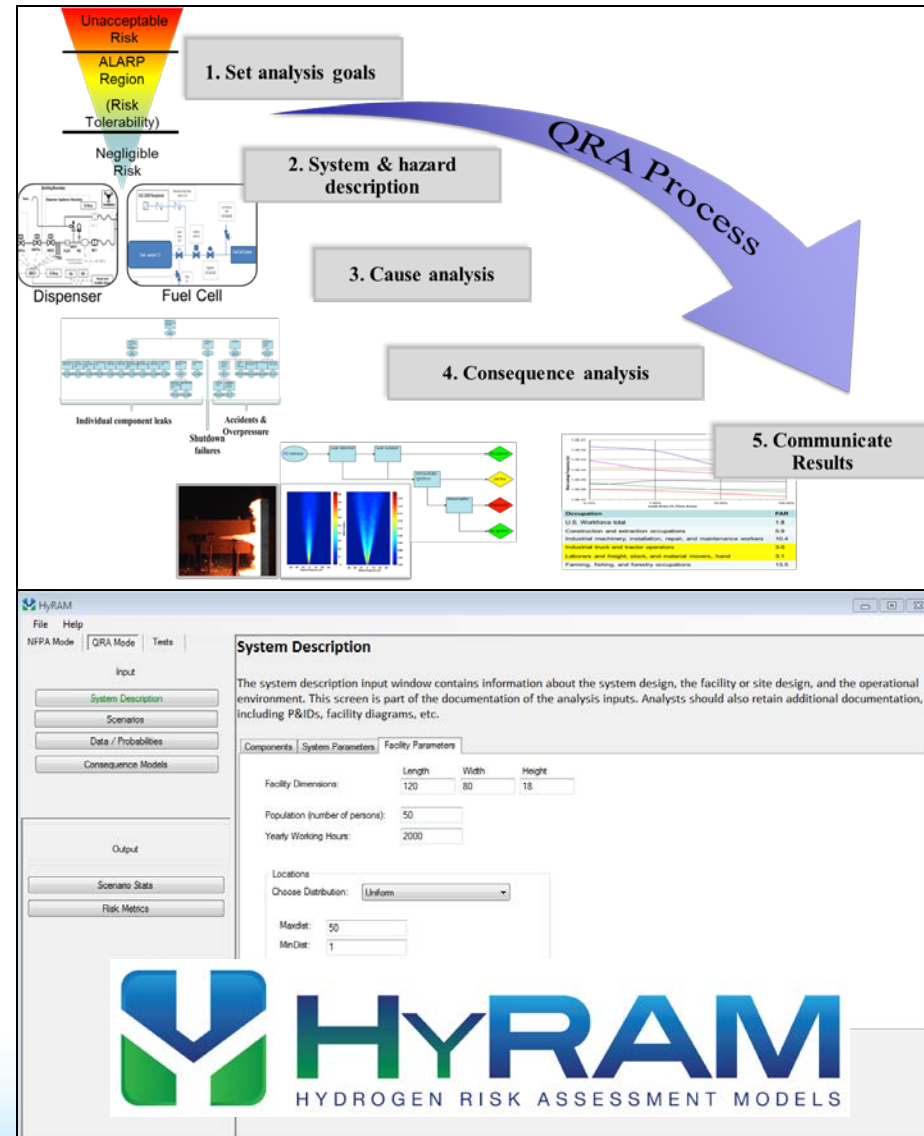
Honolulu, HI, USA

25 June 2014



Outline

- Discuss use of QRA in hydrogen fuel cell infrastructure applications
- Introduce first prototype of HyRAM toolkit



A new application for QRA: H₂ infrastructure

- Hydrogen fuel cell electric vehicles (FCEVs) gaining traction in US and international markets
 - Zero emissions
 - Fast refueling
- H₂ industry is looking to QRA to help establish a balance between safety and cost
 - Challenges: High infrastructure costs, public perception of safety



Photo credits: NREL (Top), Hydrogenics (Bottom)

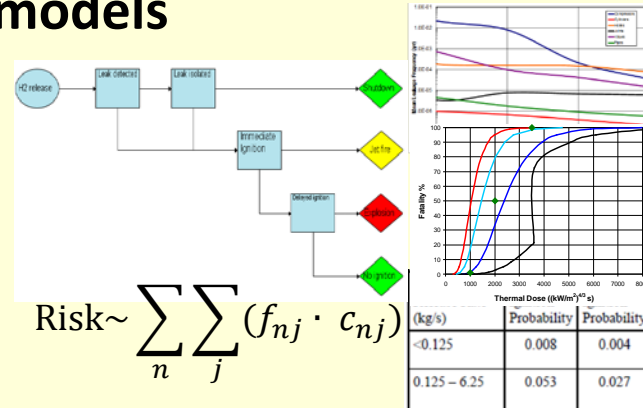
H2 codes and standards (C&S) developers want QRA

- NFPA 2 and ISO TC197 want to use QRA to refine codes
 - QRA used for NFPA 2 (*Hydrogen Technologies Code*) –
 - Station separation distances (Chapter 7)
 - Indoor fueling requirements (Chapter 10)
 - QRA can be used as “performance-based” option (e.g., NFPA2 Ch. 5)
- **Challenge 1:** Short commercial history requires the use of both deterministic and probabilistic models for QRA
 - Limited statistical data for H₂-specific component performance, leak frequencies, gas and flame detection, ignition, harm
 - Evolving understanding of H₂ physical behavior and consequences
- **Challenge 2:** Lack of user-friendly tools for doing this type of analysis

H2 researchers are rapidly filling in gaps

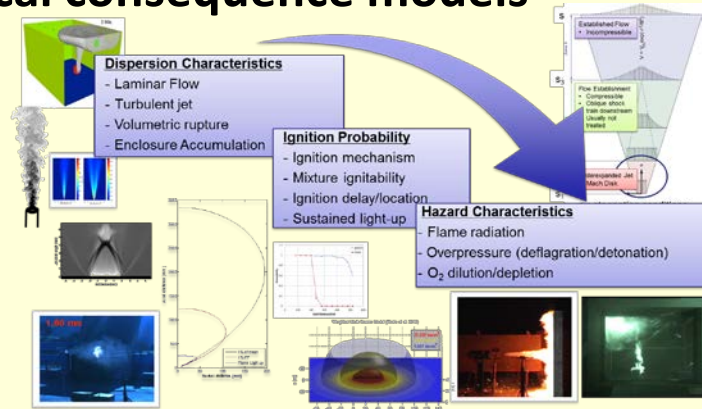
QRA method, data & models

- Hazards
- Accident sequences
- Release frequencies
- Ignition probabilities
- Harm/damage



Reduced order physical consequence models

- GH₂ release
- Ignition
- Reduced-order jet flame models
- Deflagration overpressure



Outstanding gaps: System operating experience; component failure rates; Models for LH₂ releases & cold gas plumes; ignition / flame light-up; Effect of barriers, detectors;

Sandia and HySafe are working to integrate those efforts

Objective: Facilitate H2 industry access to best science and engineering models to enable industry-lead QRAs

QRA method, data & models

- Hazards
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$$\text{Risk} \sim \sum_n \sum_j (f_{nj} \cdot c_{nj})$$

(kg/s)	Probability	Probability
-0.125	0.008	0.004
0.125 – 6.25	0.053	0.027

Reduced order physical consequence models

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Dispersion Characteristics

- Laminar Flow
- Turbulent jet
- Volumetric rupture
- Enclosure Accumulation

Ignition Probability

- Ignition mechanism
- Mixture ignitability
- Ignition delay/location
- Sustained light-up

Hazard Characteristics

- Flame radiation
- Overpressure (deflagration/detonation)
- O₂ dilution/depletion

Outstanding gaps:

System operating experience; component failure rates; Models for LH2 releases & cold gas plumes; ignition / flame light-up; Effect of barriers, detectors;

Sandia: Integrated QRA algorithm & HyRAM toolkit

System Description

The system description input window contains information about the system design, the facility or site design, and the operational environment. This screen is part of the documentation of the analysis inputs. Analysts should also retain additional documentation, including P&IDs, facility diagrams, etc.

Components | System Parameters | Facility Parameters

Facility Dimensions: Length: 100, Width: 80, Height: 10

Population Number of persons: 50

Years Working Hours: 2000

Locations: Choose Database: Urban

Model: 50

Model: 1

HySafe: Coordination of physical modeling & tools

Vertical jet centerline extent

Hydrogen	Effectiveness
Birch 1984	
Birch 1987	
Chen & Rodi - Ideal gas law	
Chen & Rodi - Abel-Noble	0.00635
Ewan and Moodie	0.09722
Houf et. al. - Ideal gas law	0.0815
Houf et. al. - Abel-Noble	0.07285
Molkov et. al. - Without Loss - Using ChenRodi	0.08937

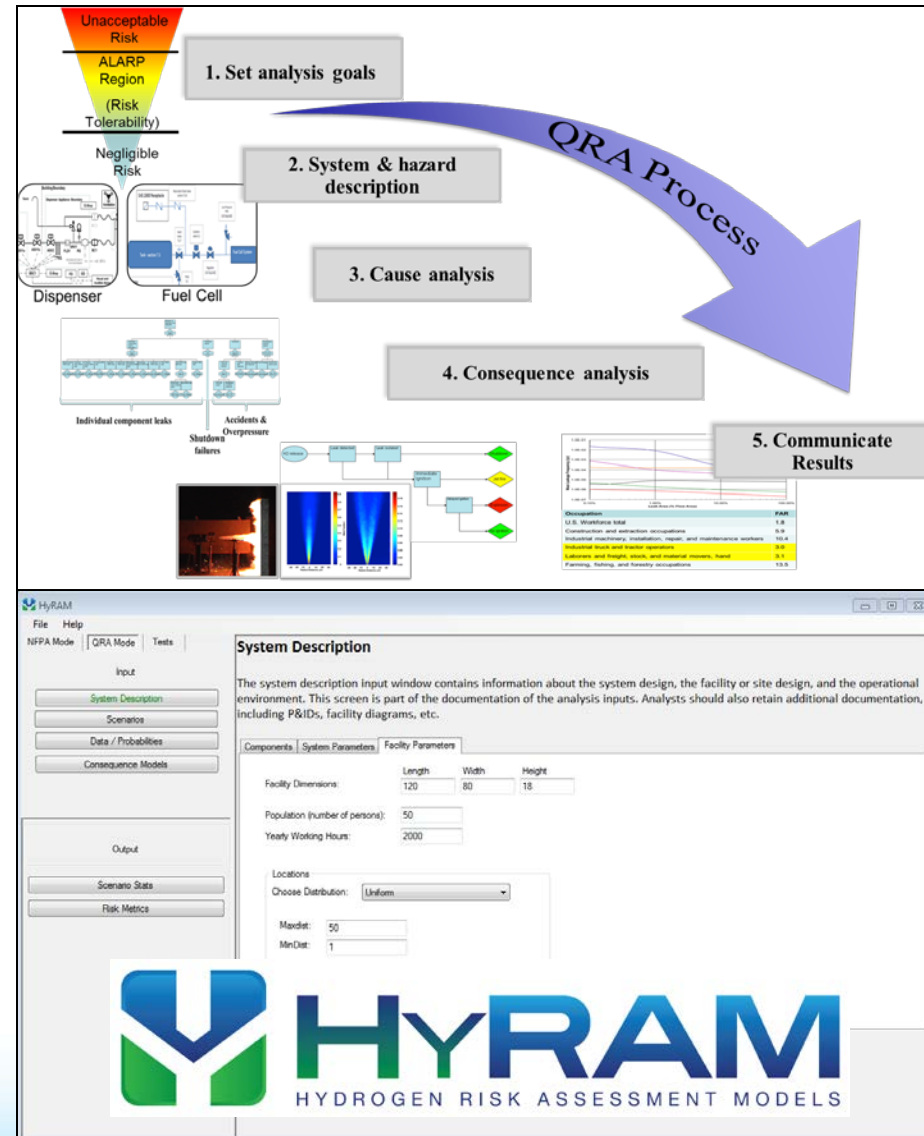
Scoping an industry-focused tool

- Sandia & HySafe workshop (June 2013) -- define user needs, goals
- Two distinct stakeholder groups.
 - **Users** – pilot the application of QRA toolkit for addressing specific industry questions.
 - High level, generic insights for C&S developers, regulators, etc.;
 - Detailed, site-specific QRA insights for system designers, insurers, authorities having jurisdiction (AHJs)
 - **Developers** – Improve the data and models being used within the toolkit.

Participation & iteration by both communities is necessary for success

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HyRAM = Hydrogen Risk Assessment Models

- **Goal:** Develop toolkit integrating state-of-the-art H2 models
 - All relevant hazards (thermal, mechanical, toxicity)
 - H2 probabilistic models and systems data
 - H2 phenomena (gas release, ignition, heat flux, overpressure)
- And use a modular software architecture to permit changes as science improves H2 understanding



Risk Metrics

Calculate the risk in terms of FAR, PLL, and AIR

Risk Metric	Value	Unit
Potential Loss of Life (PLL)	7.365e-004	Fatalities/system-year
Fatal Accident Rate (FAR)/100M exposed hours	1.682e-001	Fatalities in 10 ⁸ person-ho...
Average individual risk (AIR)	3.363e-006	Fatalities/year

- The risk metrics integrate both probability and consequences of hydrogen risk scenarios
 - FAR (Fatal Accident Rate) is the expected number of fatalities in 100million exposed hours.
 - AIR (Average Individual Risk) is the expected number of fatalities per exposed person-year.
 - PLL (Potential Loss of Life) is the expected number of fatalities per system-year.

Metrics [currently] supported in HyRAM

Calculates 3 risk metrics:

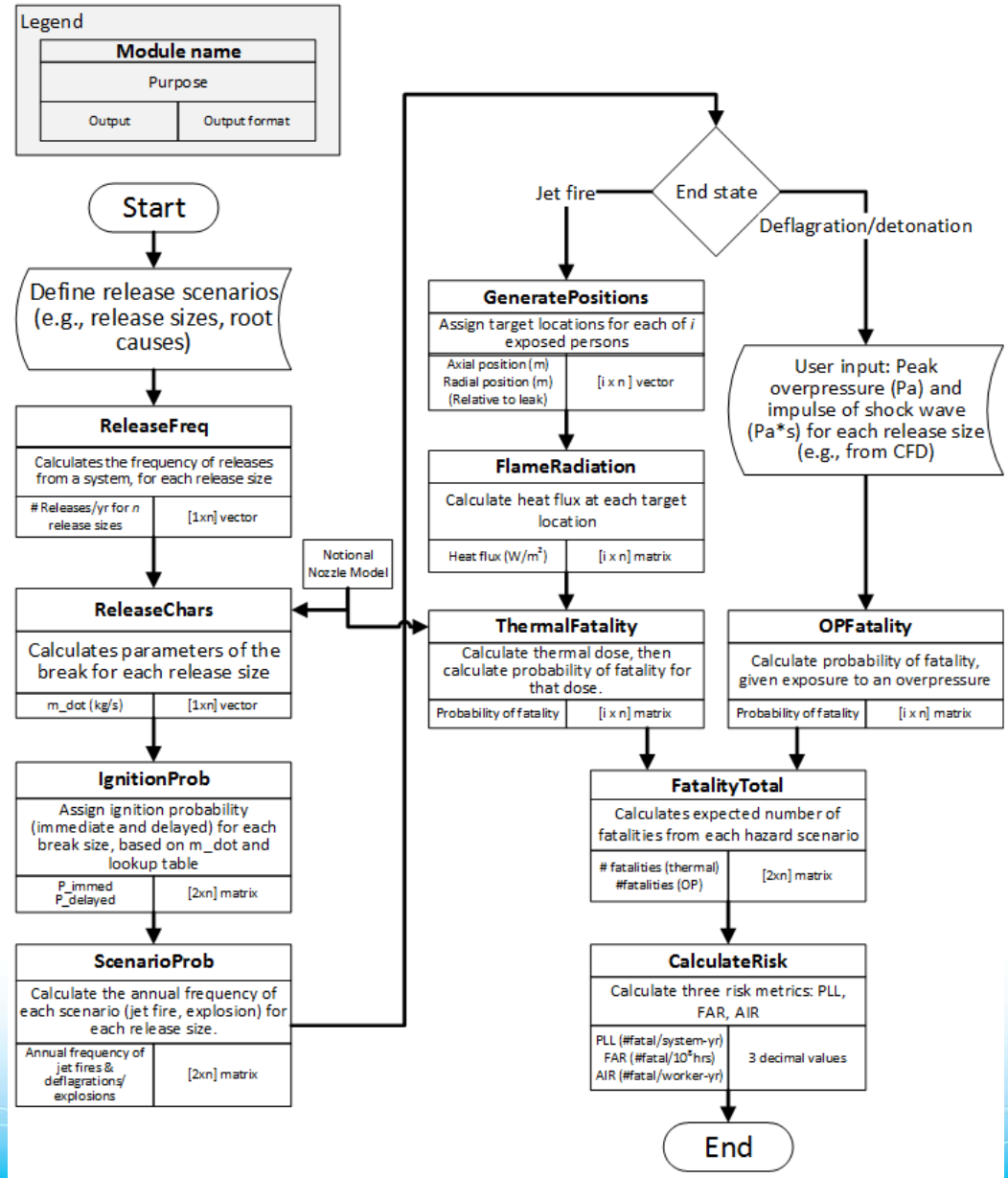
- **FAR (Fatal Accident Rate)**
 - Expected number of fatalities per 100million exposed hours
- **AIR (Average Individual Risk)**
 - Expected number of fatalities per exposed individual
- **PLL (Potential Loss of Life)**
 - Expected number of fatalities per dispenser-year.

And physical behavior of:

- **Hydrogen jets**
 - Width, velocity, density, ...
- **Jet fires**
 - Flame length, heat flux, ...
- **Deflagrations** (coming soon)
 - Ignitable volume, overpressure, ...

HyRAM toolkit modules

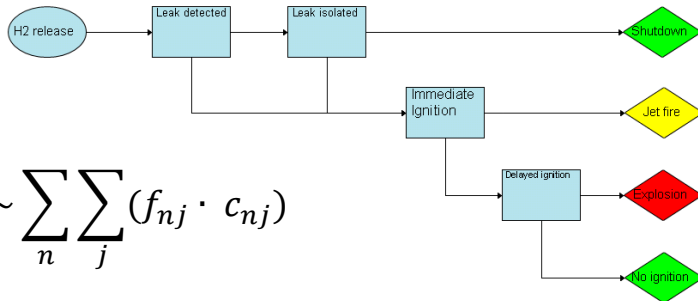
- .NET software framework (Windows) with planned HTML interface;
 - C# and Python
- Integrates best available probabilistic and deterministic models for:
 - Component failure
 - Ignition occurrence
 - Gas release
 - Gas dispersion
 - Jet flames
 - Deflagration / detonation
 - Harm to humans and structures



Modules: Cause & harm models

Accident sequences

- Hazards considered: Thermal effects (jet fire), overpressure (deflagration/detonation)



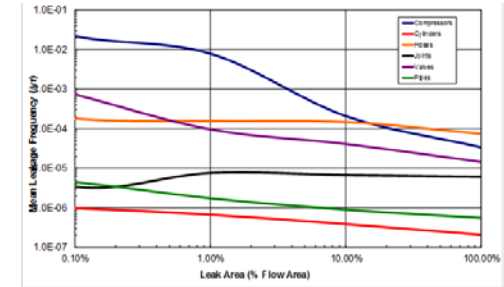
$$\text{Risk} \sim \sum_n \sum_j (f_{nj} \cdot c_{nj})$$

$$f(\text{JetFire}) = f(\text{H2release}) * (1 - \text{Pr}(\text{Detect})) * \text{Pr}(\text{IgnImmed})$$

Release frequency

- Expected annual leak freq. for each component type -- Data developed from limited H₂ data combined w/ data from other industries.

$$f(\text{H2release}) = \sum_{i=9 \text{ comps}} n_i * E(f(\text{Leak}_i)) + E(\text{Pr}(\text{accidents})) * n_{\text{demands}}$$



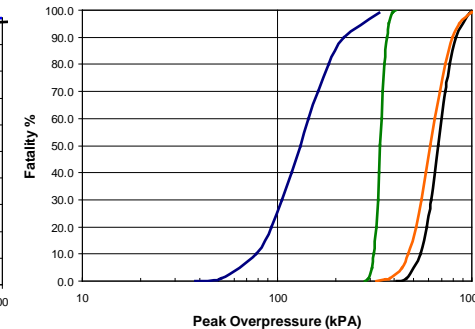
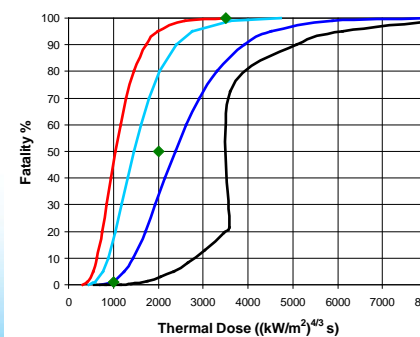
Ignition probability

- Extrapolated from methane ignition probabilities
- Flow rate calculated using *Release Characteristics* module

Hydrogen Release Rate (kg/s)	Immediate Ignition Probability	Delayed Ignition Probability
<0.125	0.008	0.004
0.125 – 6.25	0.053	0.027
>6.25	0.23	0.12

Harm models

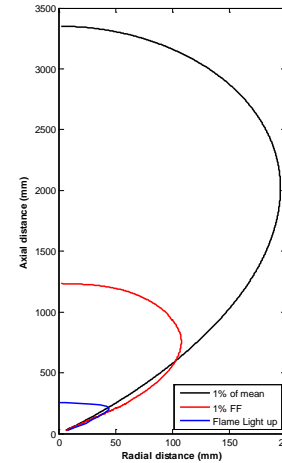
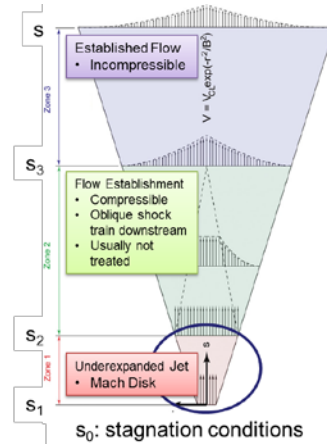
- Probability of fatality from exposure to heat flux and overpressures – multiple options



Physics Modules: Behavior & Consequence

Release Characteristics

- H₂ jet integral model developed & validated
- Source models developed for LH2 & choked flow inputs

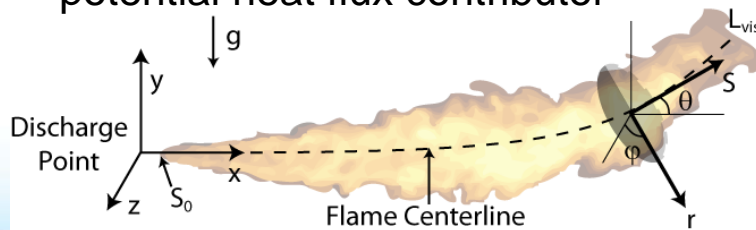


Ignition/Flame Light-up *(pending addition)*

- Flammability Factor verified for ignition prediction
- Light-up boundaries identified
- Next: sustained flame prediction

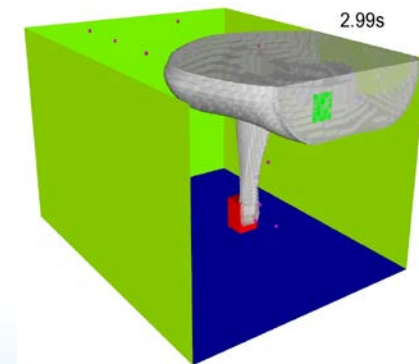
Flame Radiation

- Flame integral model developed
- Multi-source models significantly improve heat flux prediction
- Surface reflection can be a major potential heat flux contributor



Deflagration within Enclosures

- Ventilated deflagration overpressure explored experimentally and computationally
- Current QRA module requires CFD results.
- Engineering model framework pending



Next steps for the HyRAM toolkit:

- Pilot application of toolkit for NFPA2 Ch. 5 siting started Fall 2013.
- Extend algorithm scope
 - Add recent behavior models: accumulation, overpressure
 - Dynamic QRA to address variability in timing
 - Integration with international data & model selection/development efforts
- Interface development
 - Define “Physics mode”
 - Add ability to change ESDs and FTs
- Continued revision of modules as data improves
 - Collaboration with international data collection efforts

HyRAM needs from developer community

- User confidence in underlying models
- Models and data sets for H₂
 - Behavior models specifically developed & validated for application to hydrogen fuel cell problems
 - Lab-scale experiments, full-scale experiments, simulation
 - H₂ data for improving credibility of probabilistic event models (e.g., release frequencies, harm)
 - Validation activities to enhance credibility of behavior models and data originating from non-fuel-cell applications.
 - Engagement with partners to refine QRA approach, standardize, review & adopt models (international and domestic, research and application)

Summary

- Diverse group of H2 industry QRA users exists:
 - Codes & standards developers, station designers, insurers, AHJs
- Filling gaps will enable better safety analysis by H2 industry
- HyRAM toolkit being developed to facilitate use of QRA for H2
 - Continuous efforts to identify robust data and models for toolkit
 - Ongoing work to add modules, improve interfaces
 - Longer term: test problems, beta users

The image displays the HyRAM software interface on the left and a QRA process flow diagram on the right. The software interface includes a menu bar (File, Help), mode selection (NFFA Mode, QRA Mode, Tests), and several input sections: System Description (with a text area for documentation), Facility Parameters (with fields for Length, Width, Height, Population, and Working Hours), and Facility Parameters (with a dropdown for Location Distribution and fields for Mandet and MeDist). The QRA process flow diagram consists of five steps: 1. Set analysis goals, 2. System & hazard description, 3. Cause analysis, 4. Consequence analysis, and 5. Communicate Results. A large blue arrow labeled 'QRA Process' points from step 1 to step 5. A risk pyramid on the left of the diagram shows three levels: Unacceptable Risk (red), ALARP Region (Risk Tolerability) (yellow), and Negligible Risk (green). Below the pyramid are icons for a Dispenser and Fuel Cell. A small table at the bottom right of the diagram shows a risk matrix with columns for 'Risk' and 'Rank'.



Thank you!

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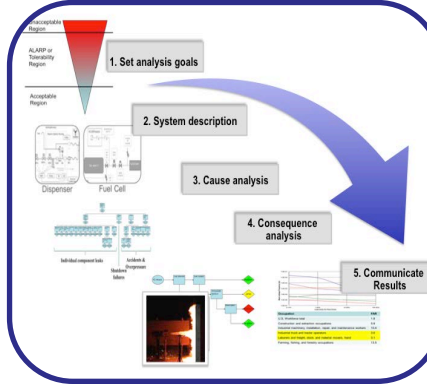
Research supported by DOE Fuel Cell Technologies Office
(EERE/FCTO)

Project overview

Objective: Develop methods, models, and tools to support the use of QRA for development & revision of RCS and safety best practices.



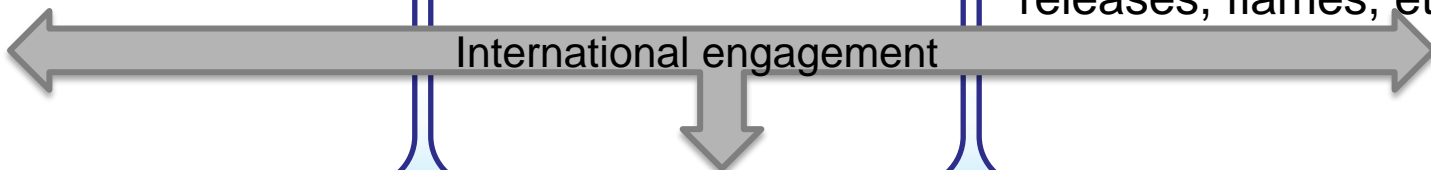
Apply risk assessment techniques in early hydrogen technologies



Develop integrated algorithms for conducting QRA for H₂ facilities and vehicles



Develop and validate scientific models to provide reduced-order information for accurate depiction of releases, flames, etc.



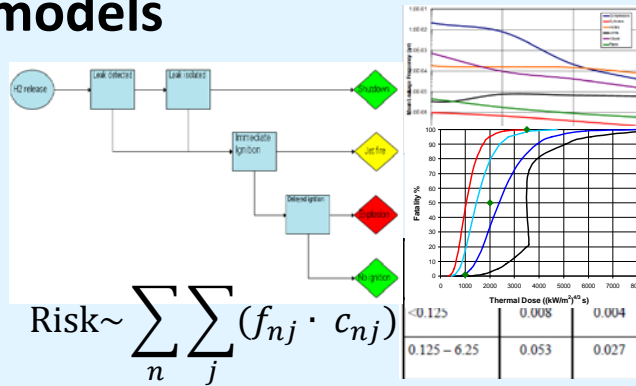
Enabling QRA tools for H₂ industry

Goals and approach

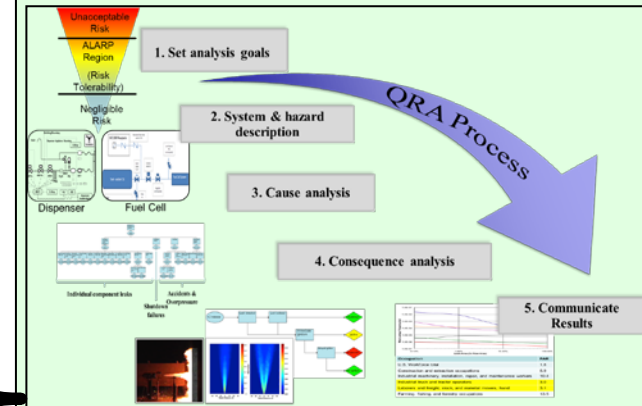
Project goals: Develop tools to facilitate industry-led use of QRA for revising and complying with H2 codes and standards

QRA method, data & models

- Hazards
- Accident sequences
- Release frequencies
- Ignition probabilities
- Harm/damage



Integrated algorithm & v0 toolkit (Matlab) (FY12-13)

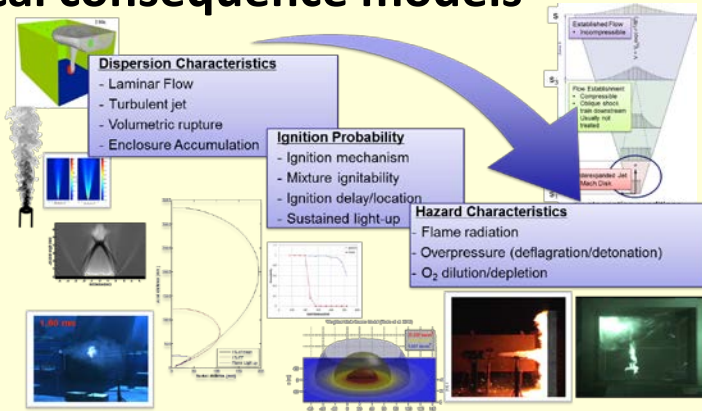


```

Y=-77.1 + 6.91*log(P_s);
case 'Lung_HSE'
HSE - Lung hemorrhage
Y=1.47+1.371*log(P_s);
case 'Head Impact'
HMO - Head impact
Y=-0.49*log((2430./P_s)+e0./ (P_s.-impulse));
case 'Collapse'
    
```

Reduced order physical consequence models

- GH₂ release
- Ignition
- Reduced-order jet flame models
- Deflagration simulation



QRA-informed C&S (FY11-13)

- Indoor fueling (NFPA2 Ch. 10)
- Station separation distances (NFPA2 Ch.7)

Hydrogen vs. hydrocarbon

- H₂ systems : High pressures (>35MPa), low temperatures (<20K) , scale (~100 components, 8mm pipe diameters),
- Hydrogen exhibits different physical behaviors than hydrocarbon fuels
 - Diffusion characteristics (Diffuses 3x faster than hydrocarbons in air)
 - Non-ideal gas behavior at high pressures or low temperatures
 - Highly buoyant
 - Very low ignition energy (an order of magnitude lower than hydrocarbons)
 - Broad flammability range (4% - 75% in air)
 - H₂ diffusion causes embrittlement in many metals
 - Lower radiative heat flux (water-only flame products, no CO₂)
 - Heat of combustion
 - More rapid generation of overpressures (and higher peak pressures) due to fast flame speed

Challenge

- CFD, PHAST, etc. are overkill for the types of insights needed for some aspects of C&S development
- Need to have a robust basis to enable consensus-based C&S development
 - Motivates need for simple quantitative methods instead of purely qualitative

QRA Gaps

1. Hydrogen-specific data for updating probability models
 - Component leak frequencies
 - Gas and flame detection probability
2. A credible probability model for ignition occurrence
3. Simplified models for predicting overpressures
4. Inclusion of human, software, & organizational failures
5. Extension to a dynamic QRA to accommodate timing, etc.
6. Software tools for NFPA2 code users