An integrated toolkit for hydrogen infrastructure risk assessment

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Probabilistic Safety Assessment and Management (PSAM 12)
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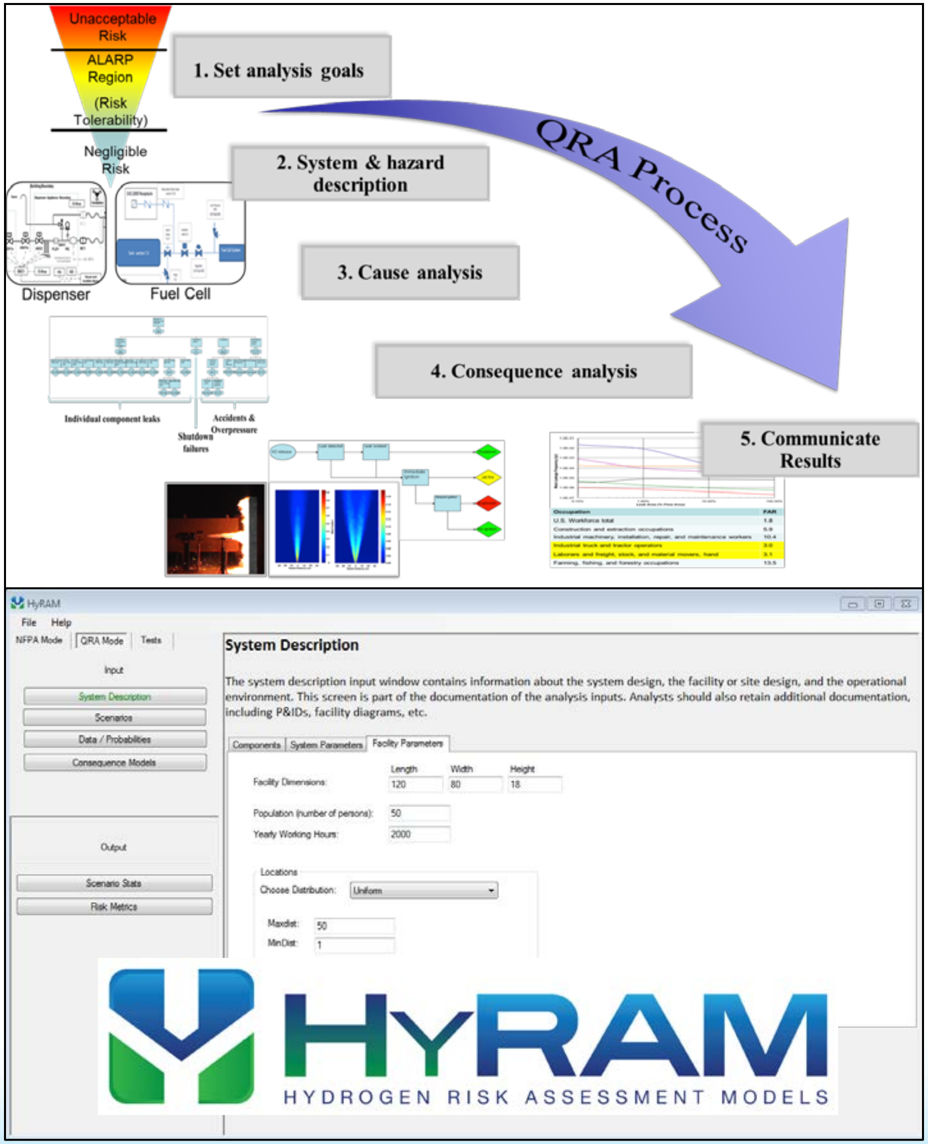
Outline

- 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

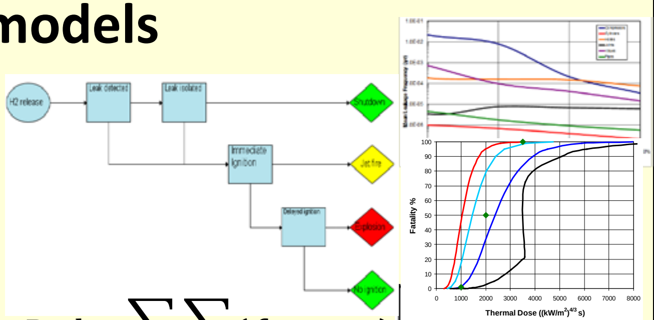
- NFPA 2 and ISO TC197 want to use QRA to refine codes
  - QRA used for NFPA 2 (*Hydrogen Technologies Code)* –
    - Station separation distances (Chapter 7)
    - Indoor fueling requirements (Chapter 10)
  - QRA can be used as “performance-based” option (e.g., NFPA2 Ch. 5)

- **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

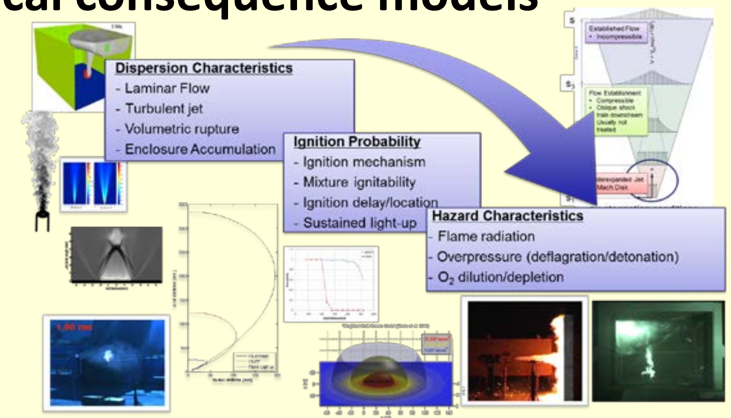


$$\text{Risk} \sim \sum_n \sum_j (f_{nj} \cdot c_{nj})$$

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

Reduced order physical consequence models

- 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

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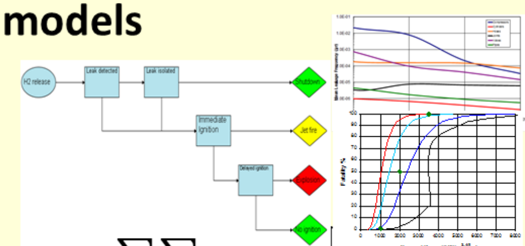

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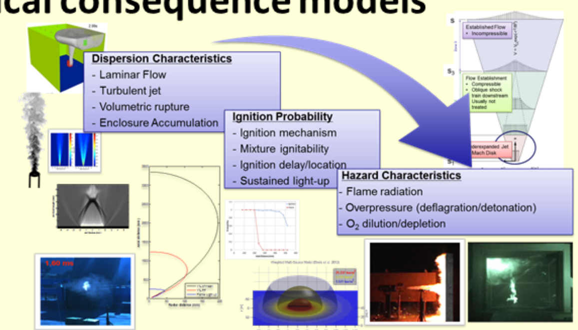

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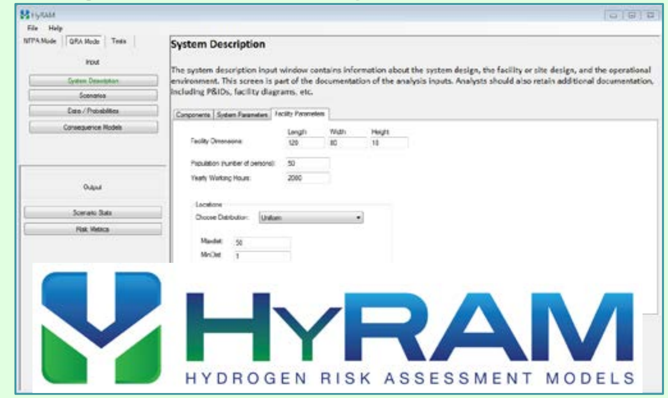
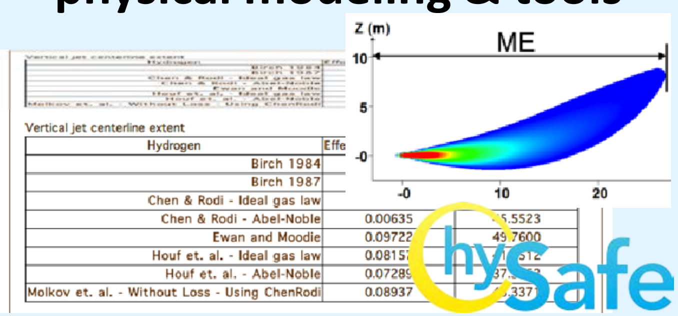
Sandia: Integrated QRA algorithm & HyRAM toolkit



HySafe: Coordination of physical modeling & tools



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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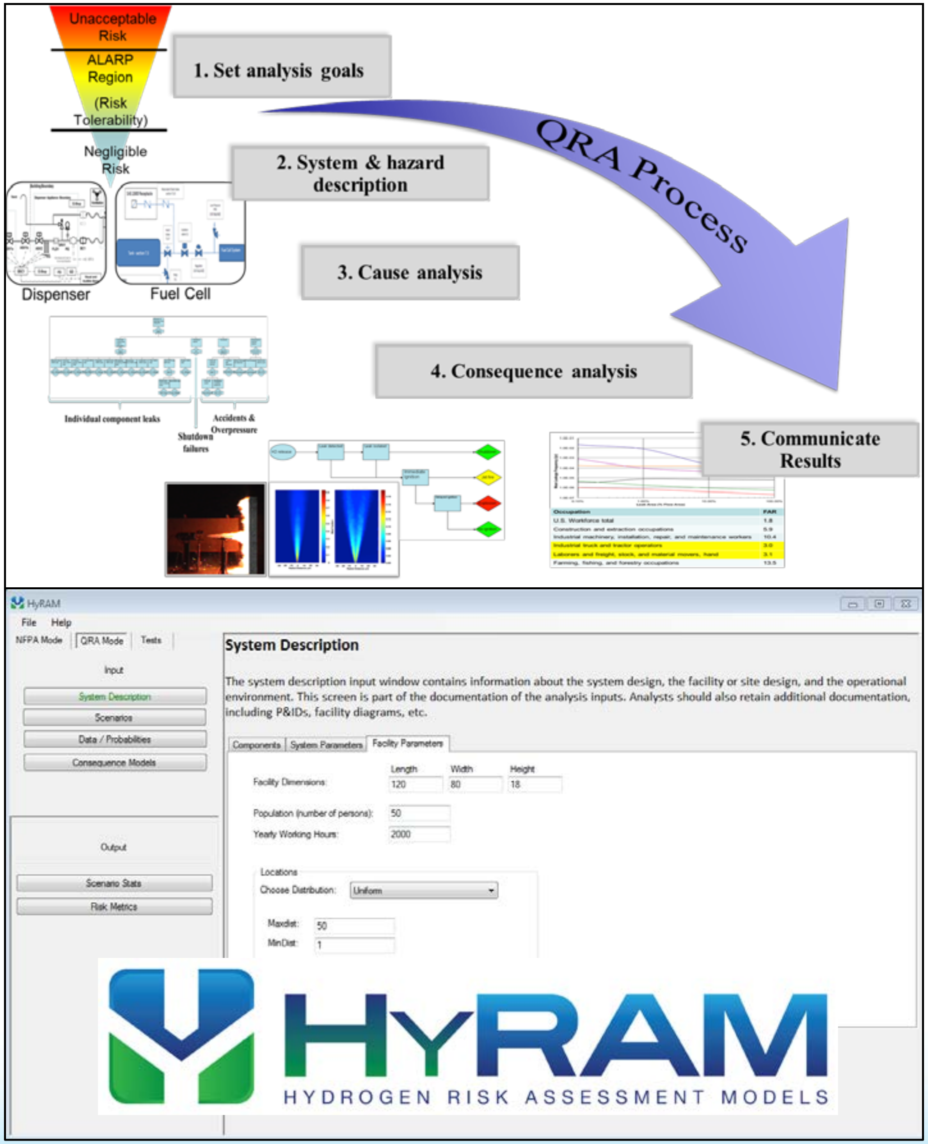
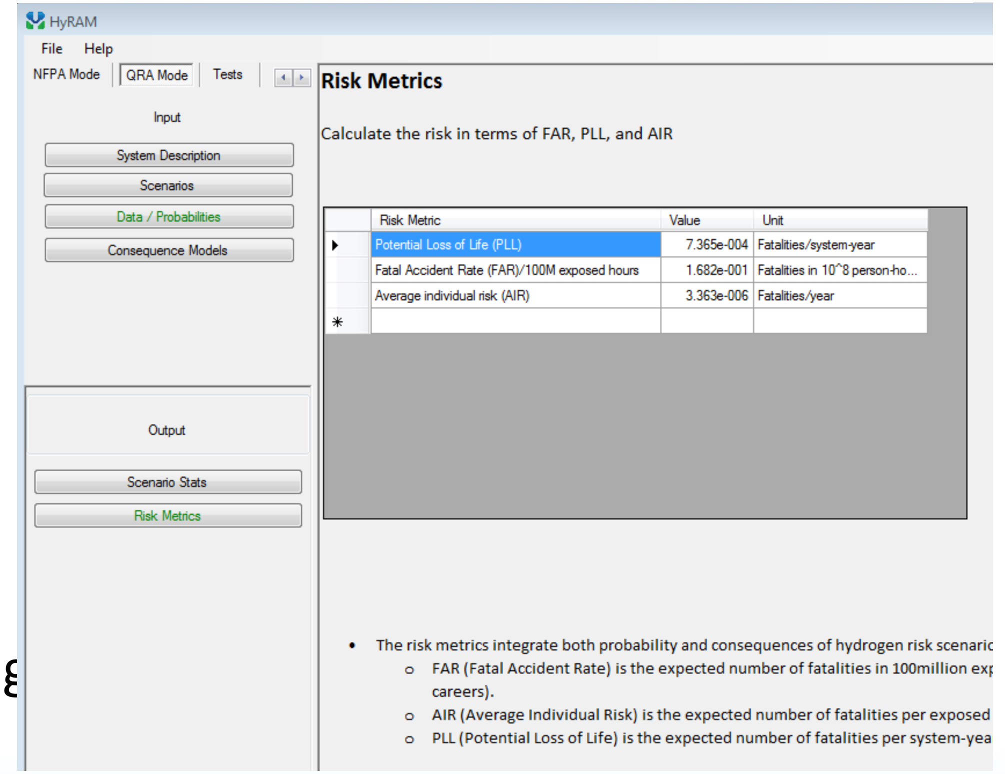


HyRAM = Hydrogen Risk Assessment Models

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



Metrics [currently] supported in HyRAM

Calculates 3 risk metrics:

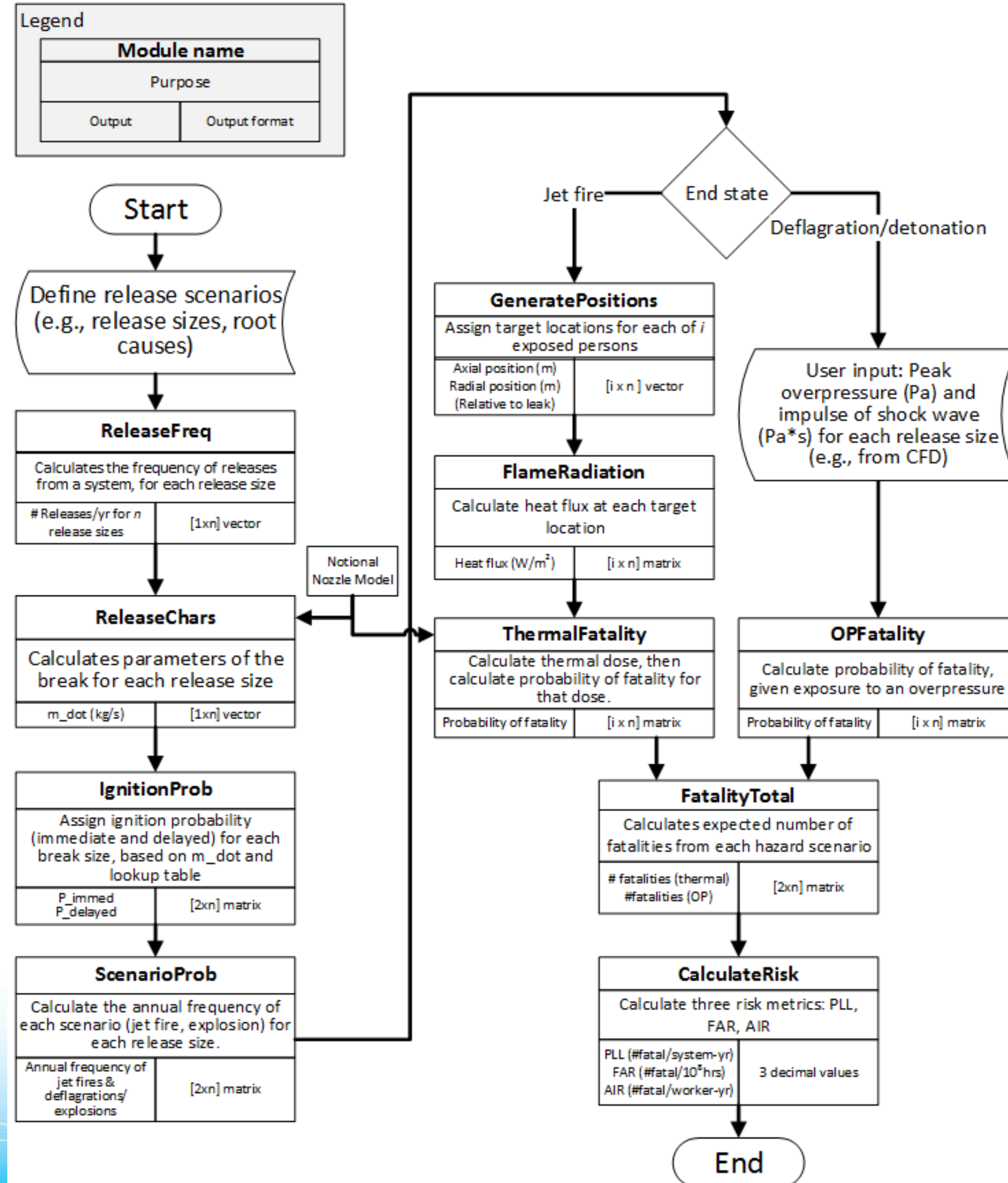
- **FAR (Fatal Accident Rate)**
  - Expected number of fatalities per 100million exposed hours
- **AIR (Average Individual Risk)**
  - Expected number of fatalities per exposed individual
- **PLL (Potential Loss of Life)**
  - Expected number of fatalities per dispenser-year.

And physical behavior of:

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

HyRAM toolkit modules

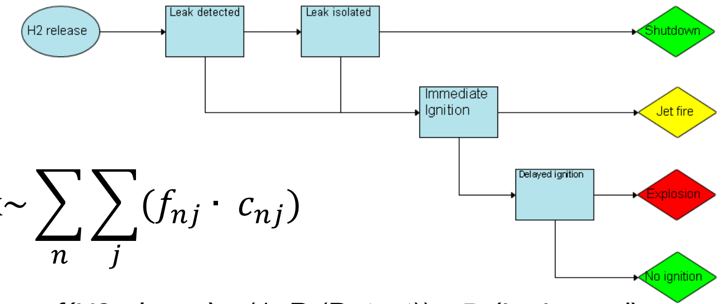
- .NET software framework (Windows) with planned HTML interface;
  - C# and Python
- Integrates best available probabilistic and deterministic models for:
  - Component failure
  - Ignition occurrence
  - Gas release
  - Gas dispersion
  - Jet flames
  - Deflagration / detonation
  - Harm to humans and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



Modules: Cause & harm models

Accident sequences

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



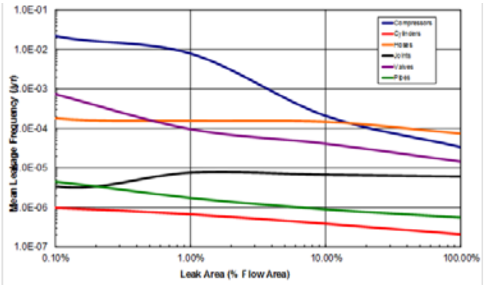
$$\text{Risk} \sim \sum_{n}\sum_{j}(f_{nj} \cdot c_{nj})$$

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

Release frequency

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

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



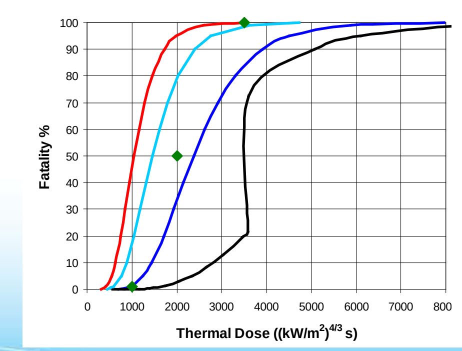
Ignition probability

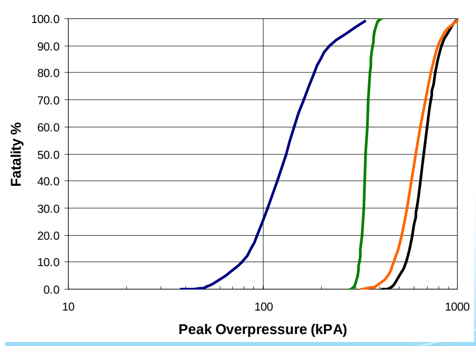
- Extrapolated from methane ignition probabilities
- Flow rate calculated using *Release Characteristics* module

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

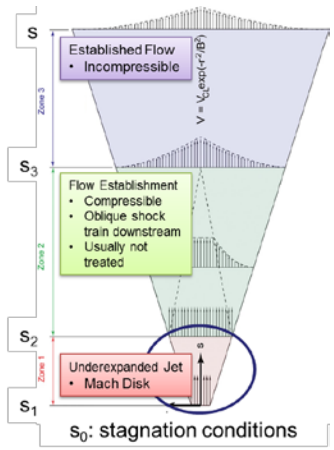


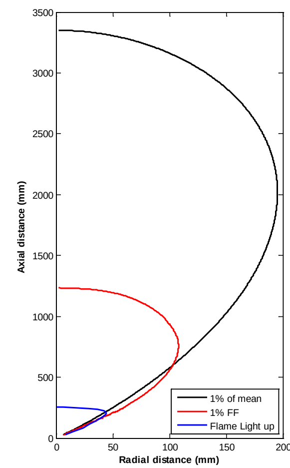


Physics Modules: Behavior & Consequence

Release Characteristics

- H_2 jet integral model developed & validated
- Source models developed for LH2 & choked flow inputs



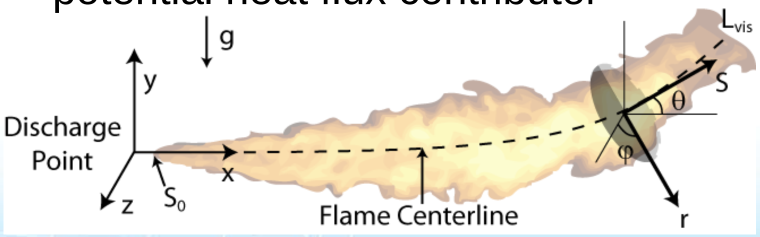


Ignition/Flame Light-up (*pending addition*)

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

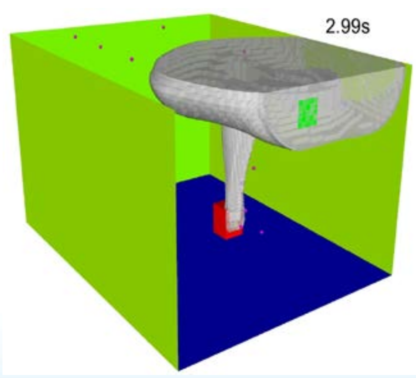
Flame Radiation

- 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

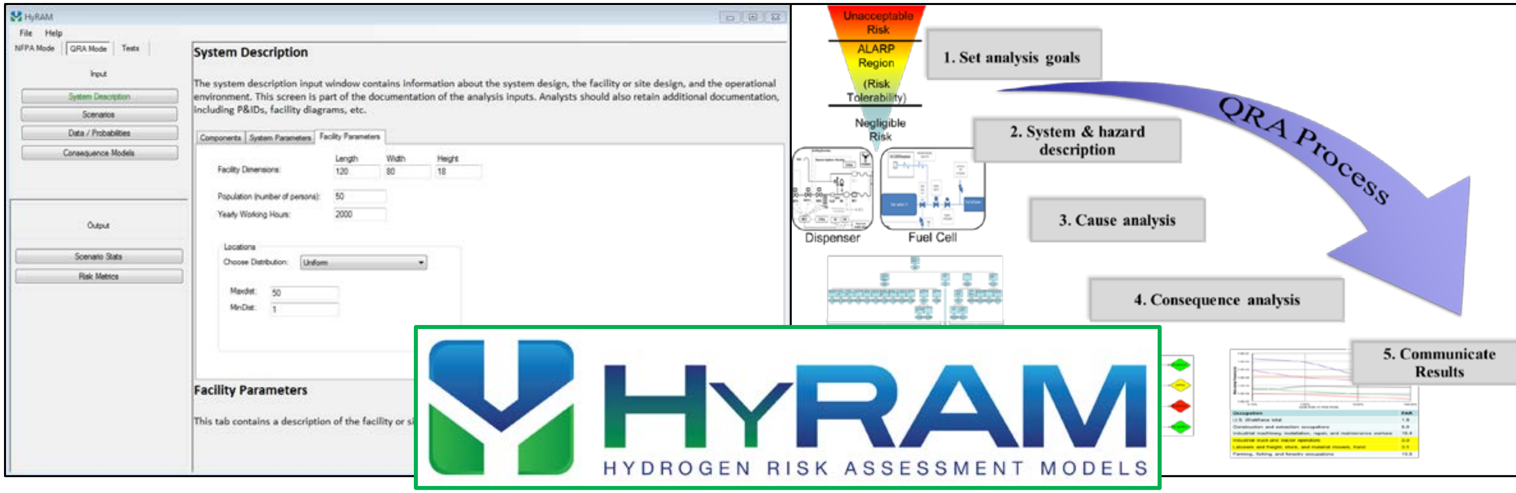
HyRAM needs from developer community

- 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



Thank you!

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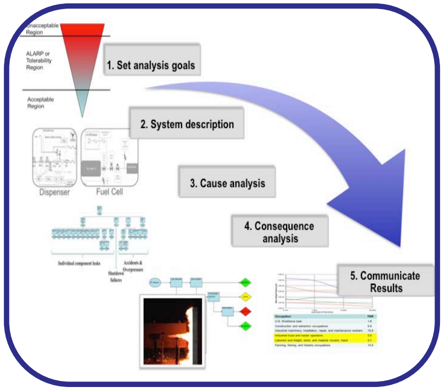
Project overview

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 H_2 facilities and vehicles

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

International engagement

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

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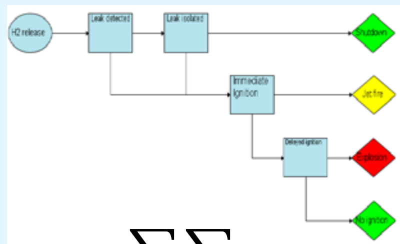

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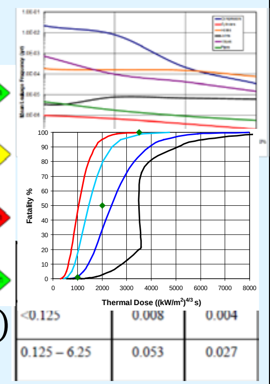

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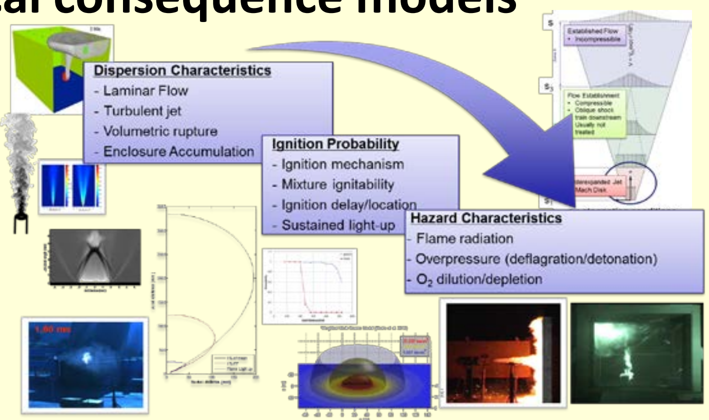
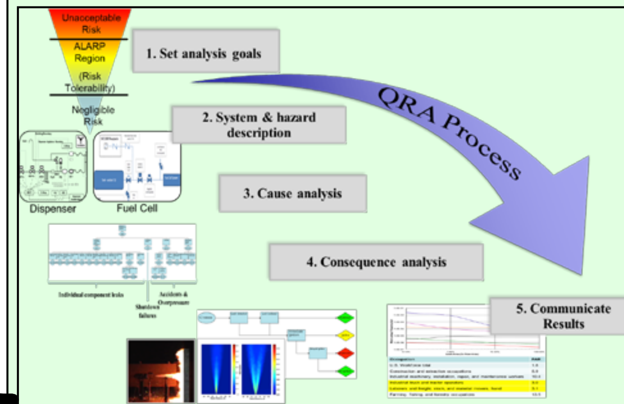


Integrated algorithm & v0 toolkit (Matlab) (FY12-13)




```
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'
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%TNO - Head impact
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Y=5-8.49*log((2430./P_s)+4e8./(P_s.*impulse));
case 'Collapse'
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

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