Hydrogen and Fuel Cells Program
SAND2015-1344PE

Introduction to Hydrogen-Specific Risk Methods and Tools

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U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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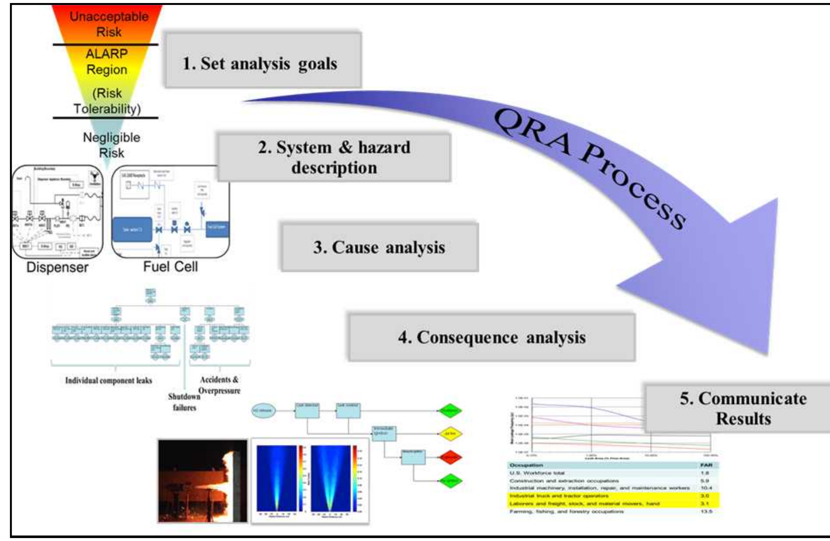
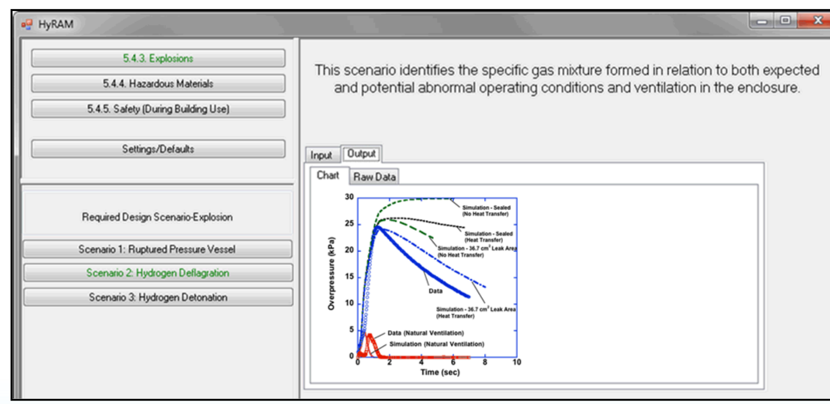
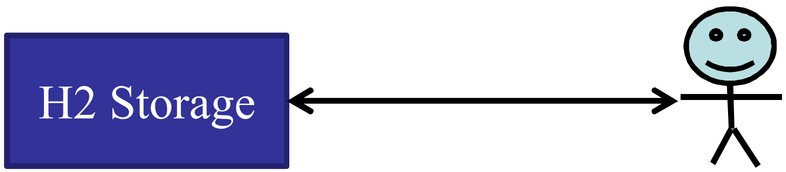
Presentation goals

- Provide an overview of the risk tools developed for NFPA 2, 2011 Edition
- Discuss how these tools will support future hydrogen risk analysis
- Open discussion for questions and feedback





Separation Distances Define Spatial Location Requirements for a Facility



- Basis for historical distances was undocumented
- Historical distances did not reflect high pressures (70 MPa) being used in indoor refueling stations

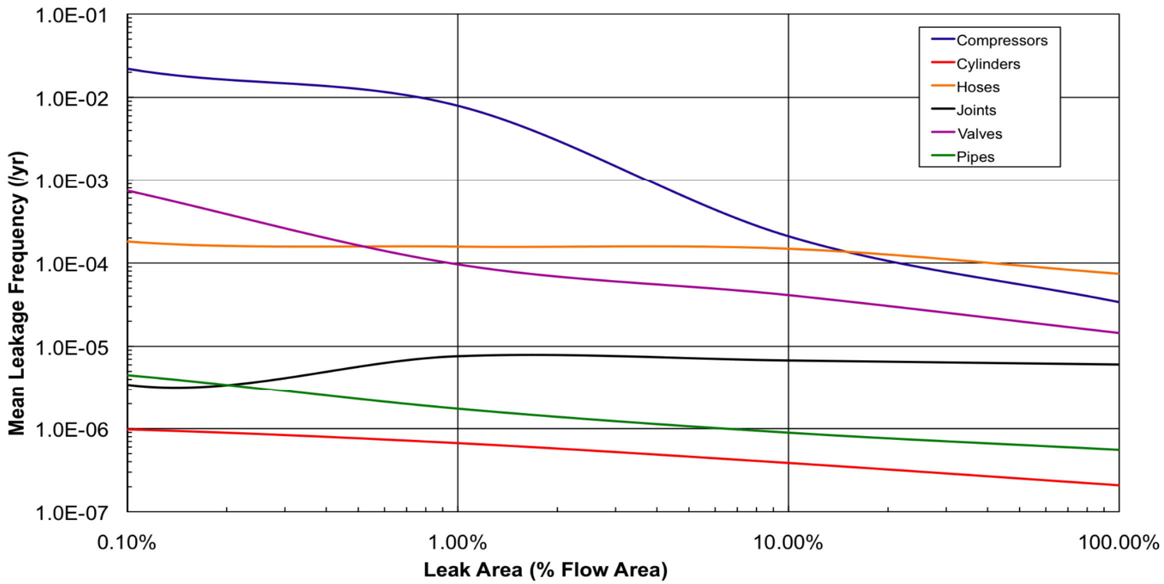
Goal: Establish that risk of fatalities in warehouse is (ALARP) As Low as Reasonably Practicable

How do we characterize risk of a hydrogen system?

- What is the chance of hydrogen getting out of the system?
- If it gets out of the system, what does that release look like? How far does it extend?
- If that release finds an ignition source, what does the resulting fire look like? How far does it extend? What is the heat flux and how far does it extend? What is the chance of an explosion?
- If a person were exposed to that heat for a certain amount of time, how bad is the injury?

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

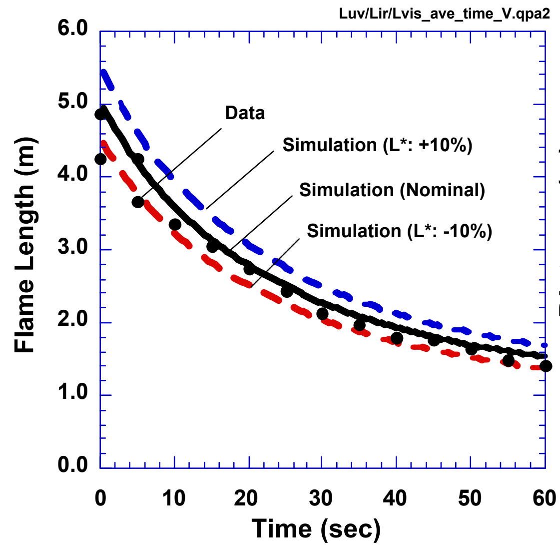
Component Leakage Frequencies Determined

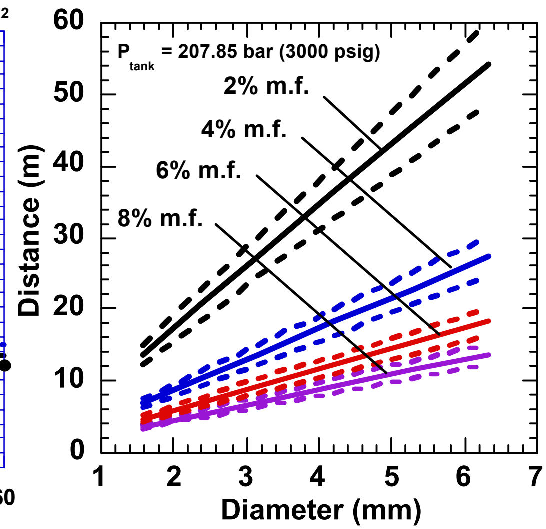


- H2-specific leak frequencies were developed by combining limited H2 data with data from other industries (using a Bayesian update)
- Leak frequencies developed for nine different types of components:
  - Compressors, cylinders, filters, flanges, hoses, joints, pipes, valves, and instruments

Sandia Hydrogen Leak Model

- Used to evaluate safety distances for hydrogen jets
- Model predicted (as function of system volume, pressure, and leak size):
  - Radiant heat flux from hydrogen jet flames
  - Visible flame length for ignited jets
  - Hydrogen concentrations in jets
- Assumes circular orifice for leak geometry and constant pressure - conservative

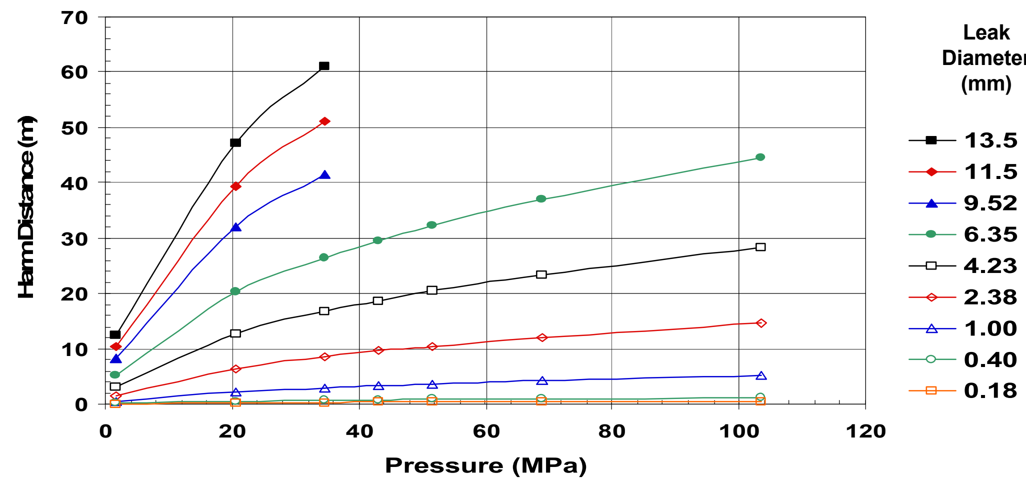


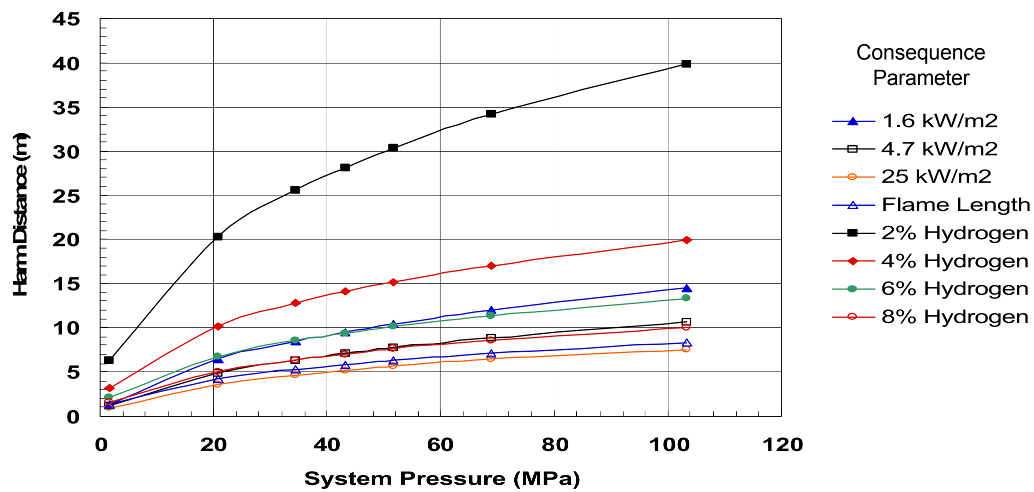


Model validated against Sandia/SRI experiments

Deterministic-Based Separation Distances Vary Significantly with Leak Diameter

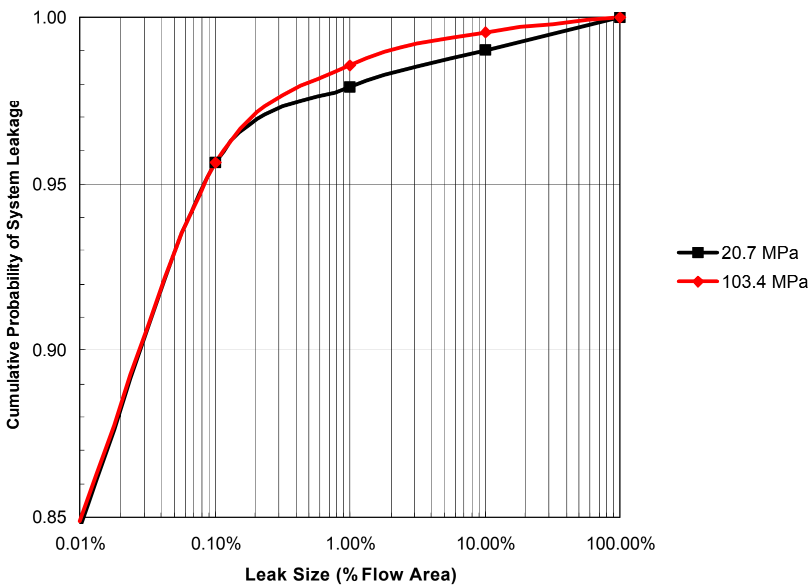
Hazard Distances for a Jet Fire: 1.6 kW/m² Radiation Heat Flux

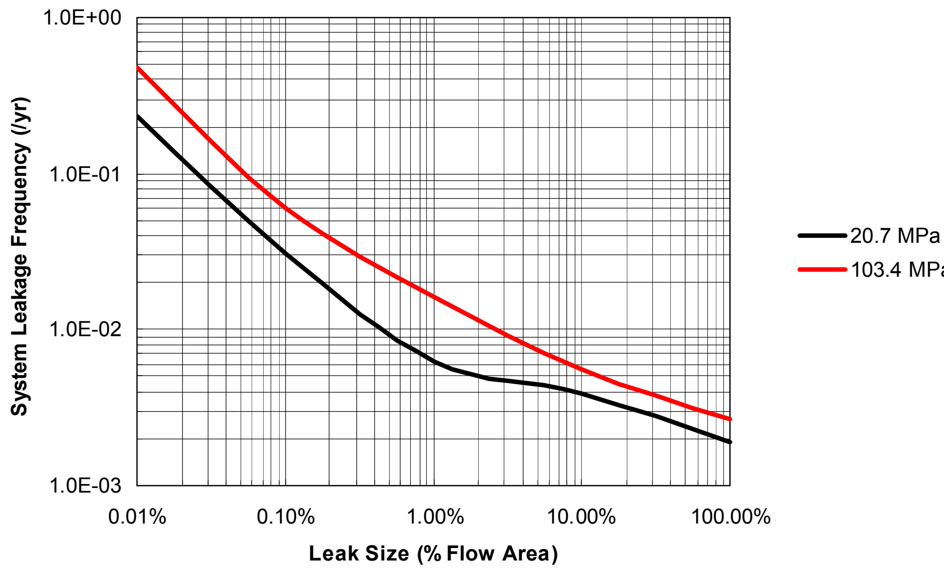




Hazard Distances for Different Consequence Measures: 2.38 mm Leak

Component Leak Frequencies Used to Determine Cumulative System Leakage Probability



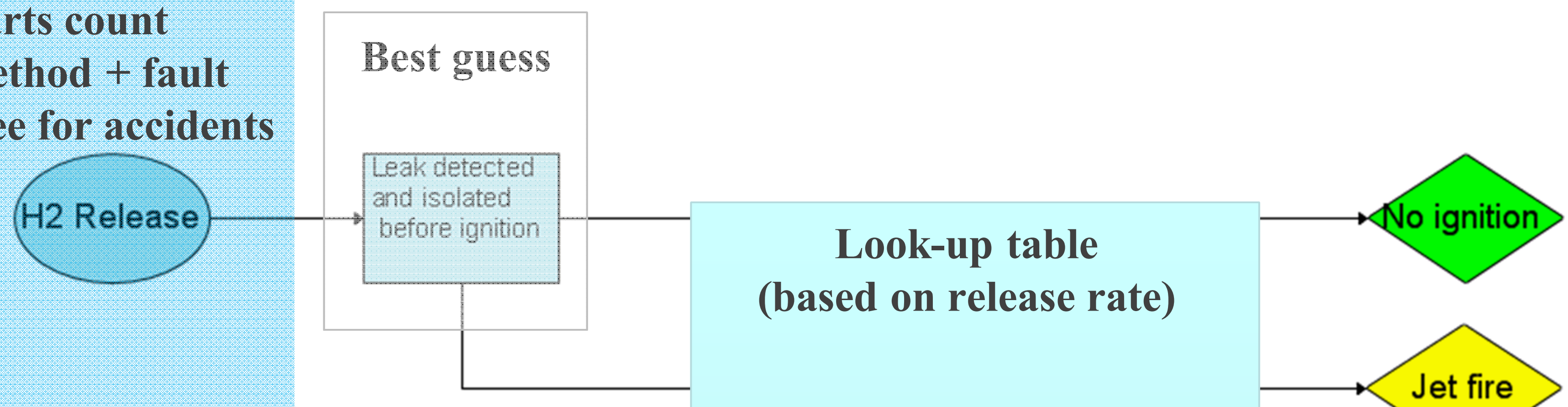


Expert opinion used to select 3% of system flow area:

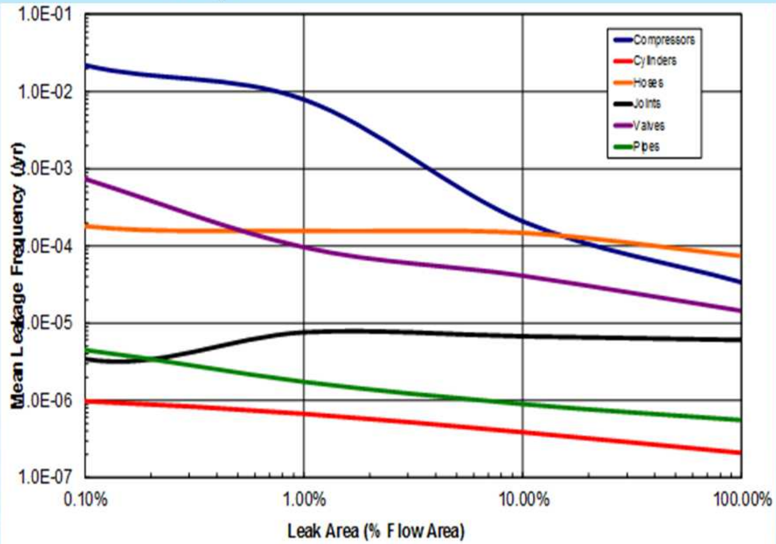
- captures >95% percent of the leaks
- the resulting separation distances protect up to the 3% leak size
- QRA performed to determine if associated risk from leaks greater than this is acceptable

Frequency calculations

Parts count method + fault tree for accidents



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

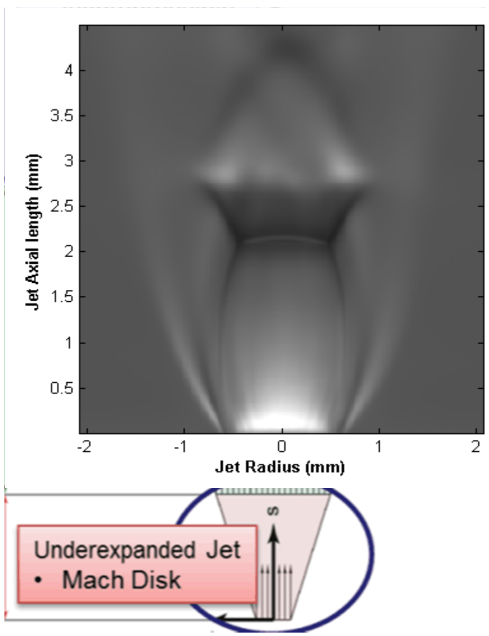


Hydrogen Release Rate (kg/s)	Immediate Ignition Probability	Delayed Ignition Probability
<0.125	0.008	0.004
0.125 – 6.25	0.053	0.027
>6.25	0.23	0.12

Consequence models

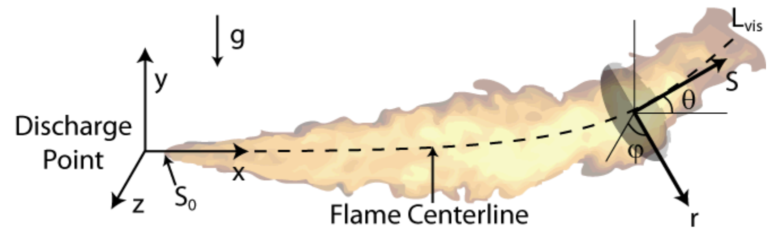
Release behavior

- First-order model for choked-flow releases
- (*Ruggles & Ekoto 2012*)
  - Experimentally validated
- Inputs: Release diameter, dispenser parameters



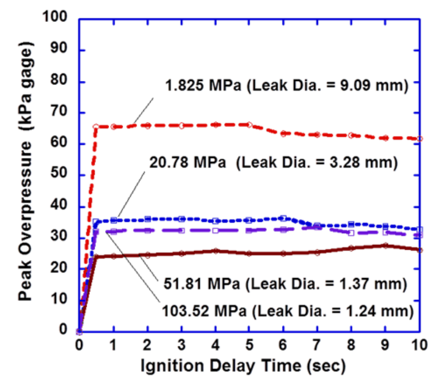
Heat flux

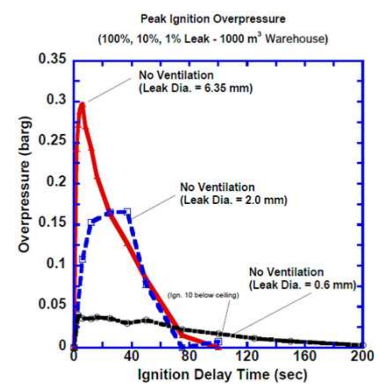
- Multi-source models (*Houf & Schefer 2007*)
  - Experimentally validated
- Inputs: release behavior, axial and radial distance from flame



Peak overpressure

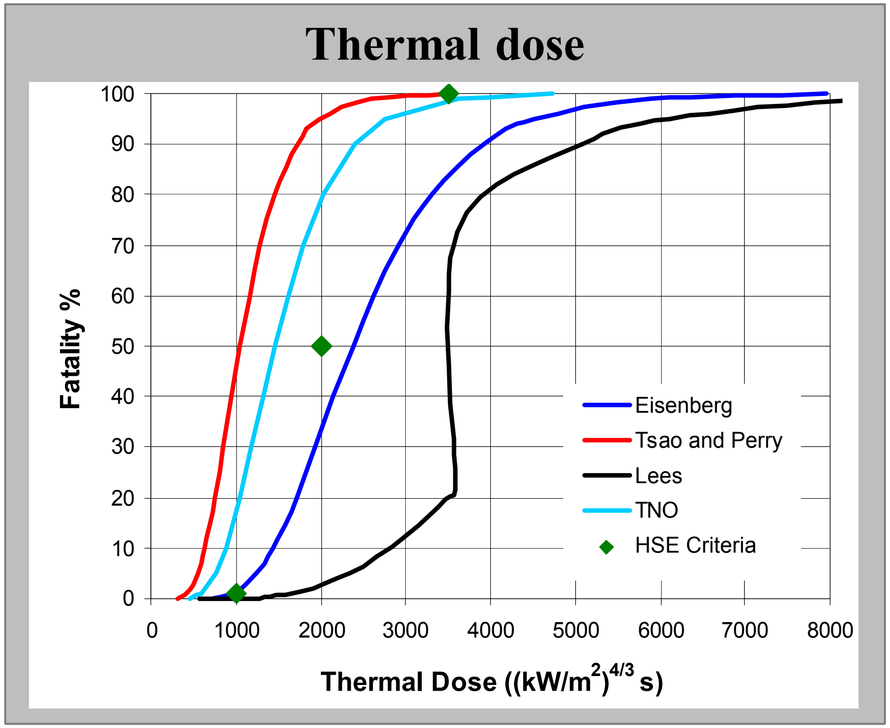
- CFD models (FLACCS/FUEGO)

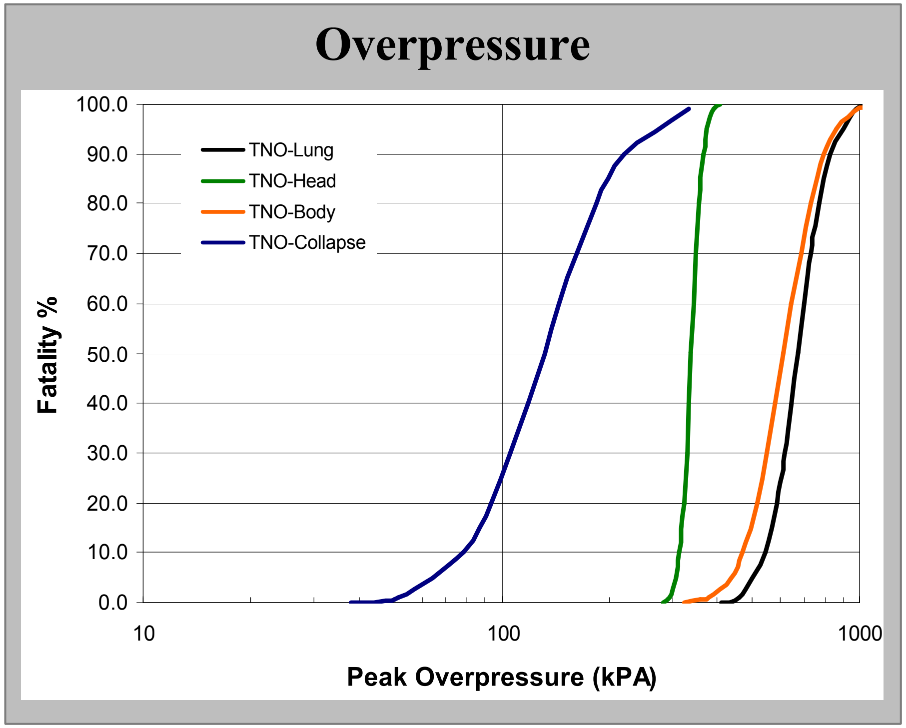




Harm models

- Probit models used to predict probability of a fatality, given…





- Summed over population of the warehouse (randomly positioned)

Define Risk Values

Calculate 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.

US Gasoline Stations

Member of Public (Used in NFPA 2): PLL or AIR below 2×10^{-5} fatalities/station-yr

Based on 2 fatalities/yr and 100,000 refueling stations in the US

Workers: One order of magnitude higher than public risk 1×10^{-4}

Average Individual Risk (CDC actuarial data 2005)

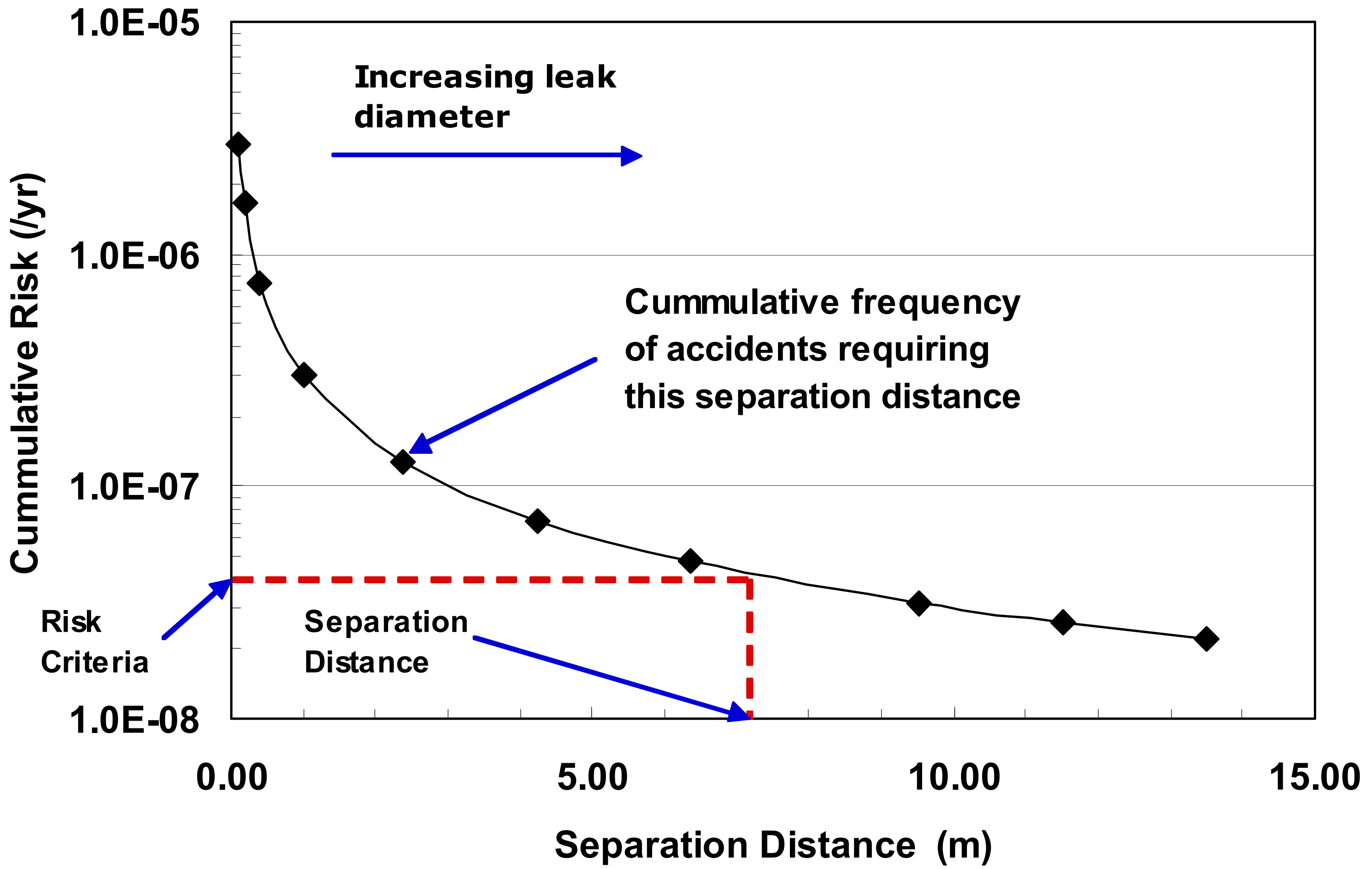
= (9117,809 Deaths/Year)/296,748,000 Total U.S. Pop.

= 4×10^{-4} Deaths/Person-Year (~ 1/2,500 Deaths/Person-Year)

In any given year, approximately 1 out of every 2,500 people in the entire U.S. population will suffer an accidental death

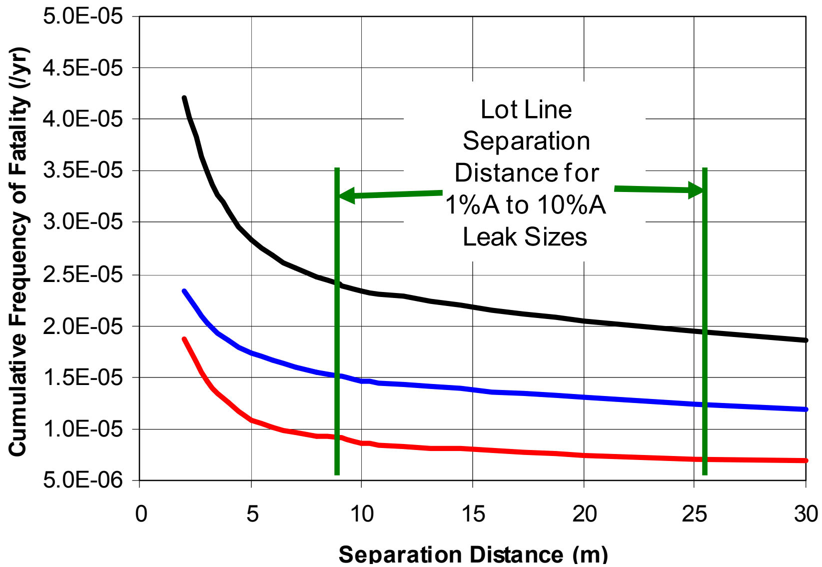
Norwegian Petroleum Directorate guidelines use a total frequency of 5×10^{-4}/yr for all accidents for all safety functions

Risk Approach for Establishing Adequacy of Safety Distances

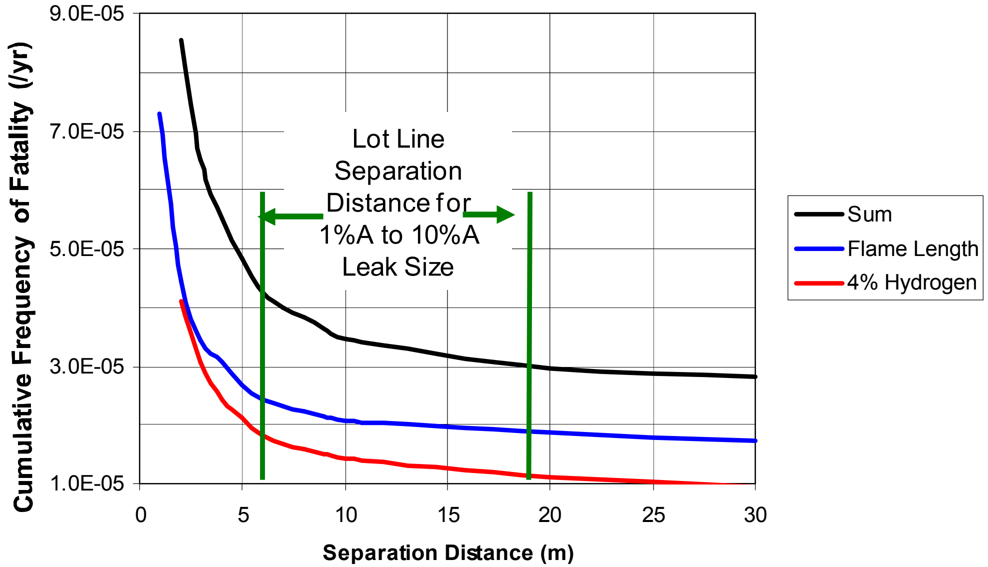


Risk Results for Representative Systems

Total Risk 20.7 MPa (3000 psig) System



Total Risk 103.4 MPa (15000 psig) System



- Risk close to the “guideline” of 2E-5 fatalities/yr selected by NFPA Task Group
- Risk from leaks greater than 3% of flow area were deemed acceptable

This Effort Validated the Risk-Informed Approach for Establishing Requirements

- NFPA 55 voted to accept the new hydrogen bulk storage separation distances table
  - New table approved for NFPA 55 and 52 (available in 2011 Editions)
  - New table included in NFPA 2 (2011 Edition)
  - HIPOC supported inclusion in IFC by referencing back to the new table in NFPA 55 (available in 2010 edition of IFC).
- ISO adopted a similar approach which provides similar results when same data is utilized in the QRA models.

This work provided a model for additional codes and standards development efforts:

- *Requirements related to mitigation features (e.g., barriers)*
- *Requirements related to indoor refueling*

Presentation goals

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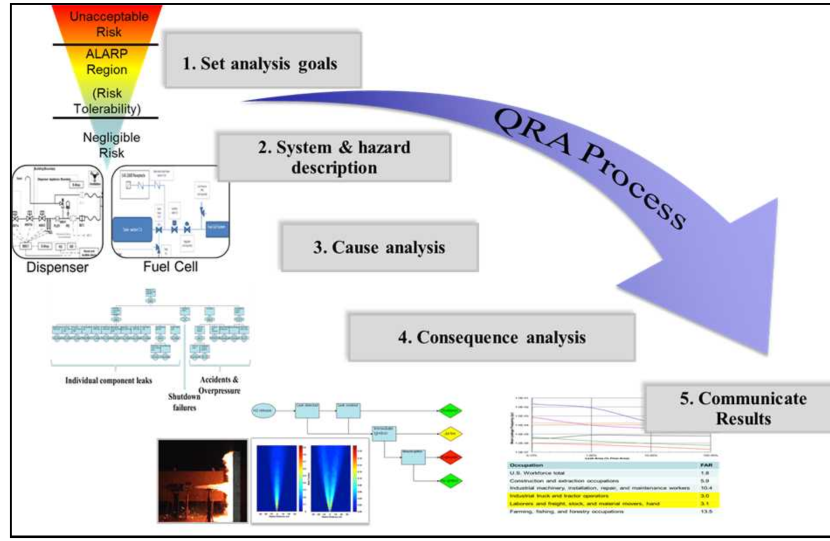
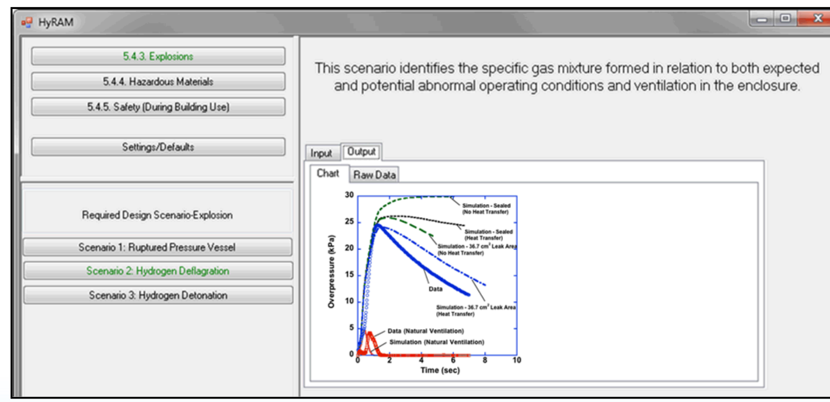
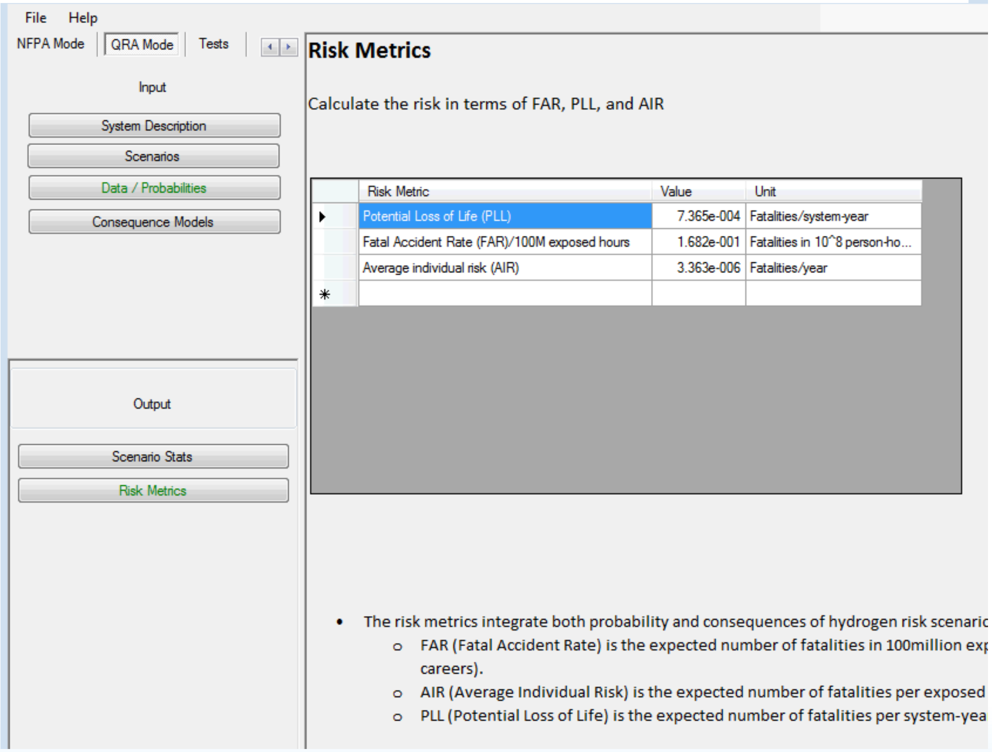




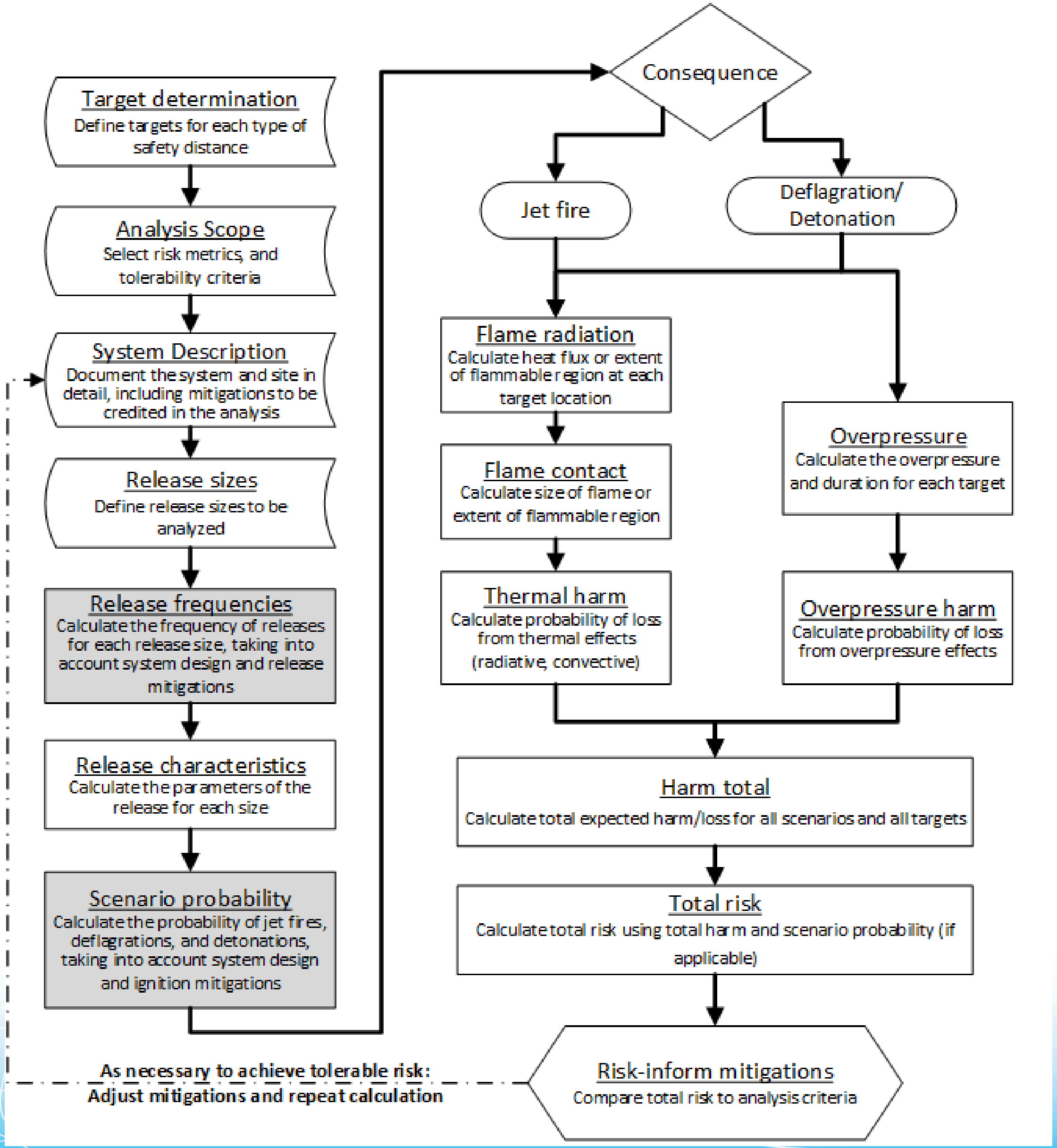
QRA Toolkit: Hydrogen Risk Assessment Models (HyRAM)

HYRAM HYDROGEN RISK ASSESSMENT MODELS

- Includes best-available models for:
  - All relevant hazards (thermal, mechanical, toxicity)
  - Probabilistic models & data
  - H2 phenomena (gas release, ignition, heat flux, overpressure)
- GUIs and generic assumptions
- Flexible software architecture to enable improvements as H2 science, data and models improve



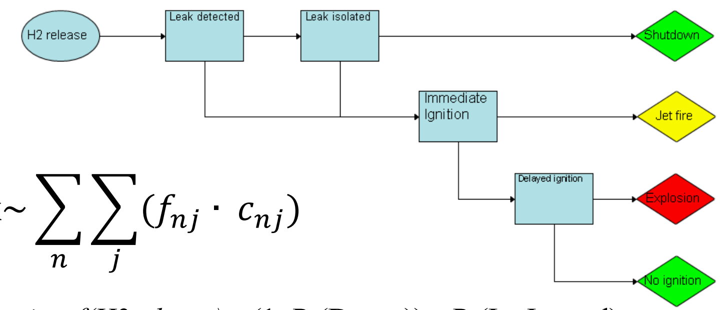
HyRAM toolkit modules



Modules: Cause & harm models

Accident sequences

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



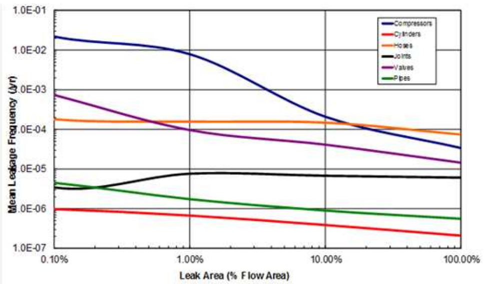
$$\text{Risk} \sim \sum_{n} \sum_{j} (f_{nj} \cdot c_{nj})$$

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

Release frequency

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

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



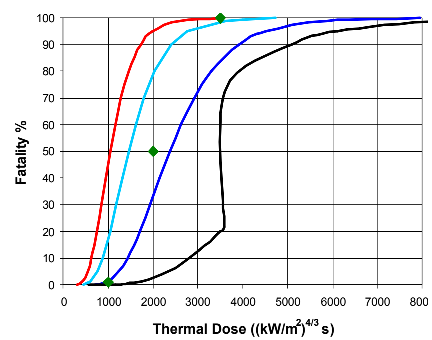
Ignition probability

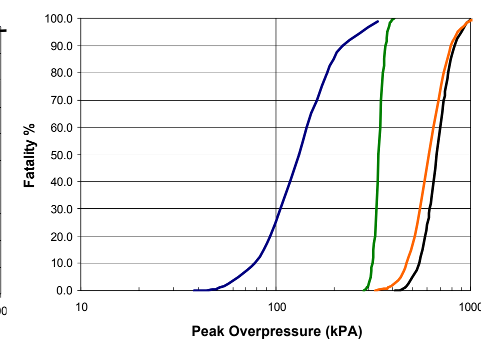
- Extrapolated from methane ignition probabilities
- Flow rate calculated using *Release Characteristics* module

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

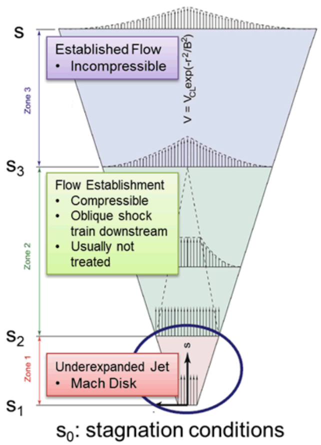


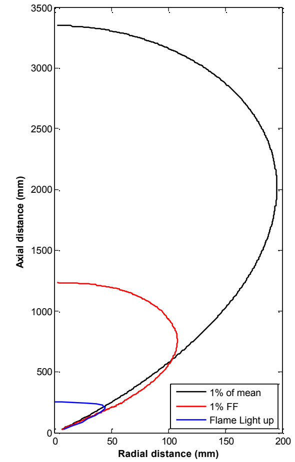


Physics Modules: Behavior & Consequence

Release Characteristics

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



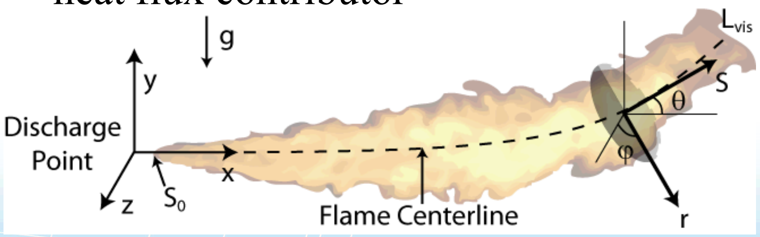


Ignition/Flame Light-up (*pending addition*)

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

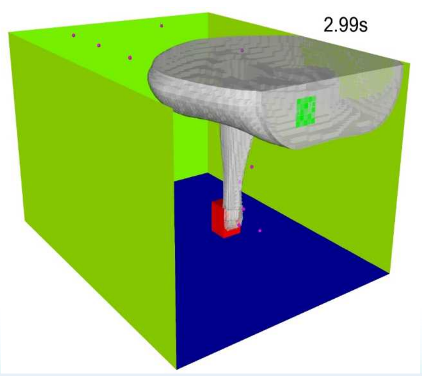
Flame Radiation

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



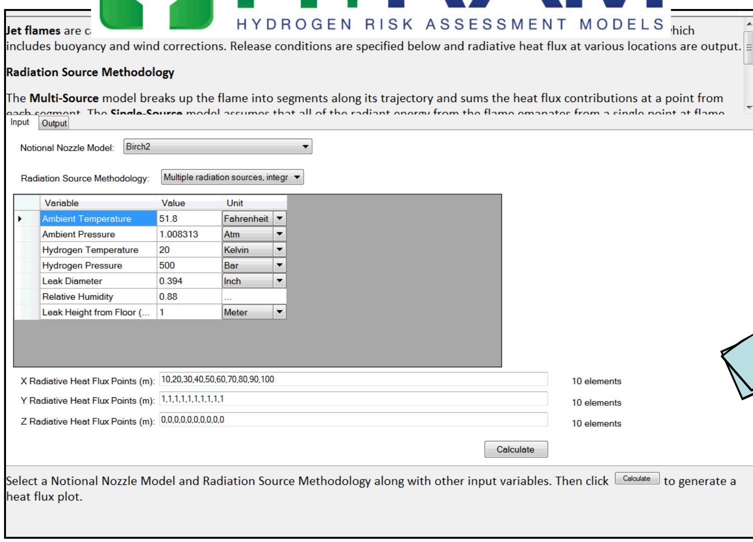
Deflagration within Enclosures

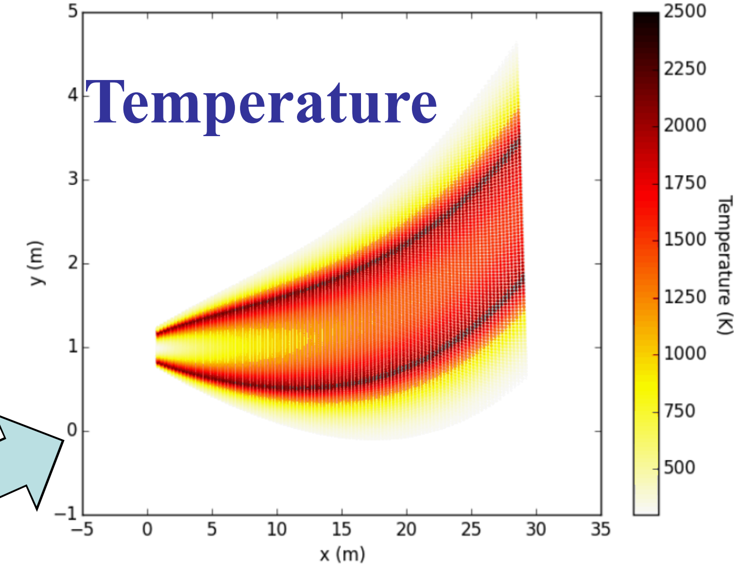
- Ventilated deflagration overpressure explored experimentally and computationally
- Current QRA module requires CFD results.
- Engineering model framework pending



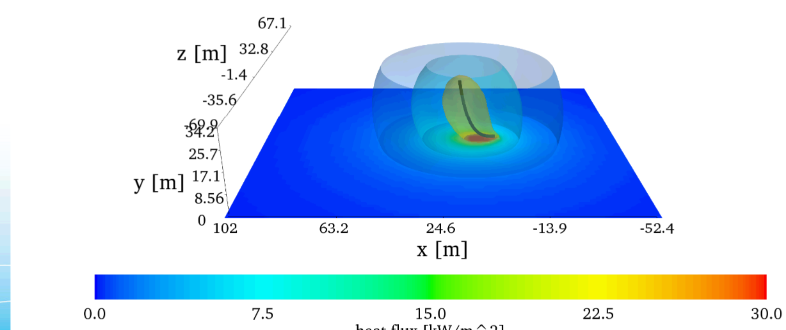
Physics Mode: Jet Fire Results

HyRAM
HYDROGEN RISK ASSESSMENT MODELS





Heat Flux



X (m)	Y (m)	Z (m)	Flux (kW/m^2)
10	1	0	60.6425
20	1	0	14.9494
30	1	0	6.1824
40	1	0	3.1225
50	1	0	1.8102
60	1	0	1.1583
70	1	0	0.7962
80	1	0	0.5771
90	1	0	0.4357
100	1	0	0.3395

Scenario – understand the flame effects for a known leak size, known conditions

Future Applications and Impacts on Codes

- Future Applications
  - Short term – basis for performance-based designs where prescriptive distances cannot be met
  - Next code cycles: science-based revision of prescriptive bulk liquid separation distances
  - Harmonization of international codes
- Current status
  - <HyRAM 1.0alpha> is ready for user (evaluation/verification) testing
  - Additional models and features are being integrated into HyRAM
- Next steps (technical)
  - Add consequence (physics) models: overpressures, cryogenic releases
  - Add risk features: sensitivity analysis root cause models, additional data, dynamic (simulation) elements for scenarios
  - Add quantitative assessment of mitigation(s)
  - Software testing & transition

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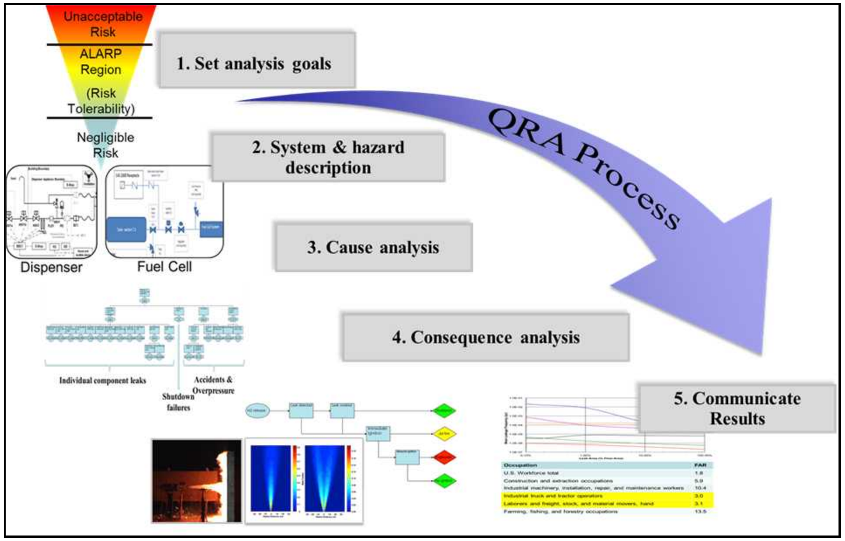

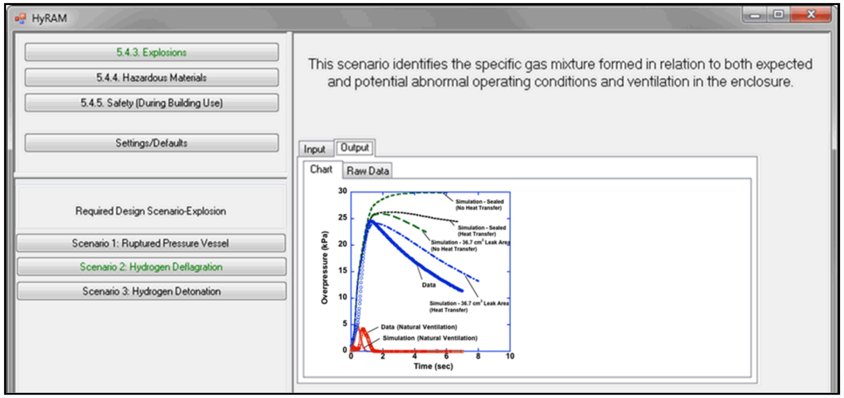

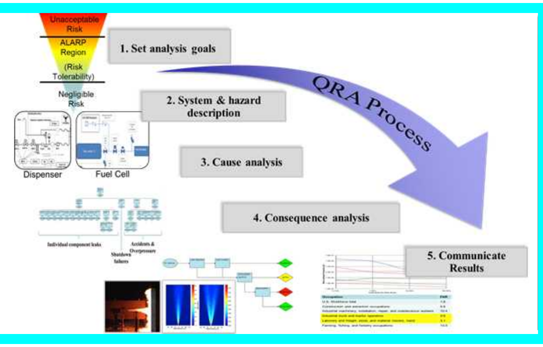

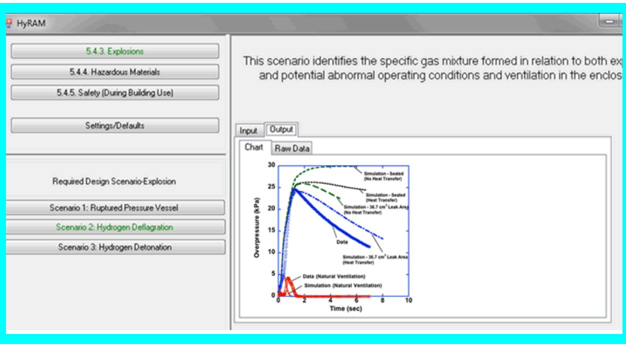

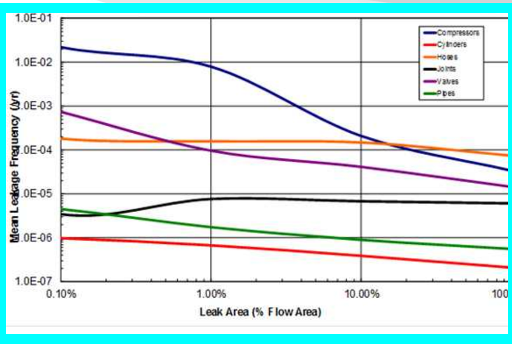

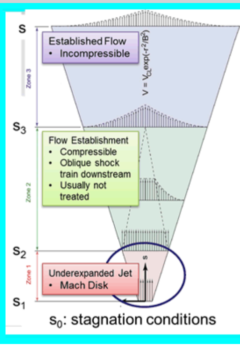

Thank you!

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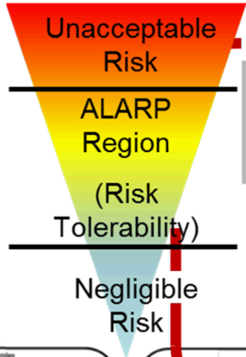
Hydrogen vs. hydrocarbon

- 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)
  - Higher heat of combustion
  - More rapid generation of overpressures (and higher peak pressures) due to fast flame speed

QRA Process Overview

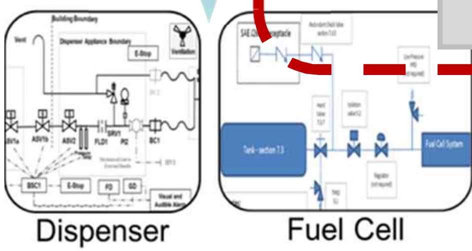


1. Set analysis goals

Before the Toolkit

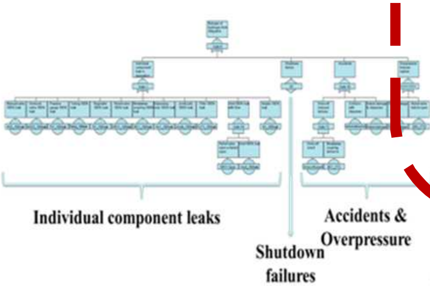
QRA Process

2. System & hazard description

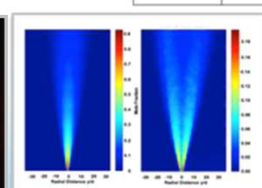


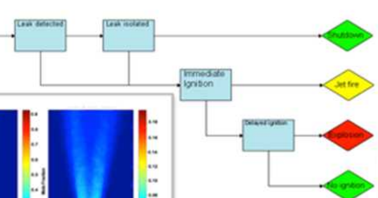
3. Cause analysis

Focus of Toolkit

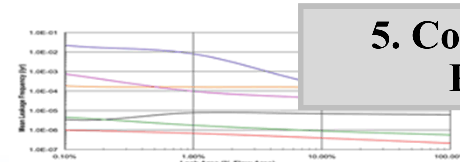


4. Consequence analysis





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