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H2 safety integration toolkits: HyRAM Version 1.0

Katrina M. Groth

Sandia National Laboratories, Albuquerque, NM, USA

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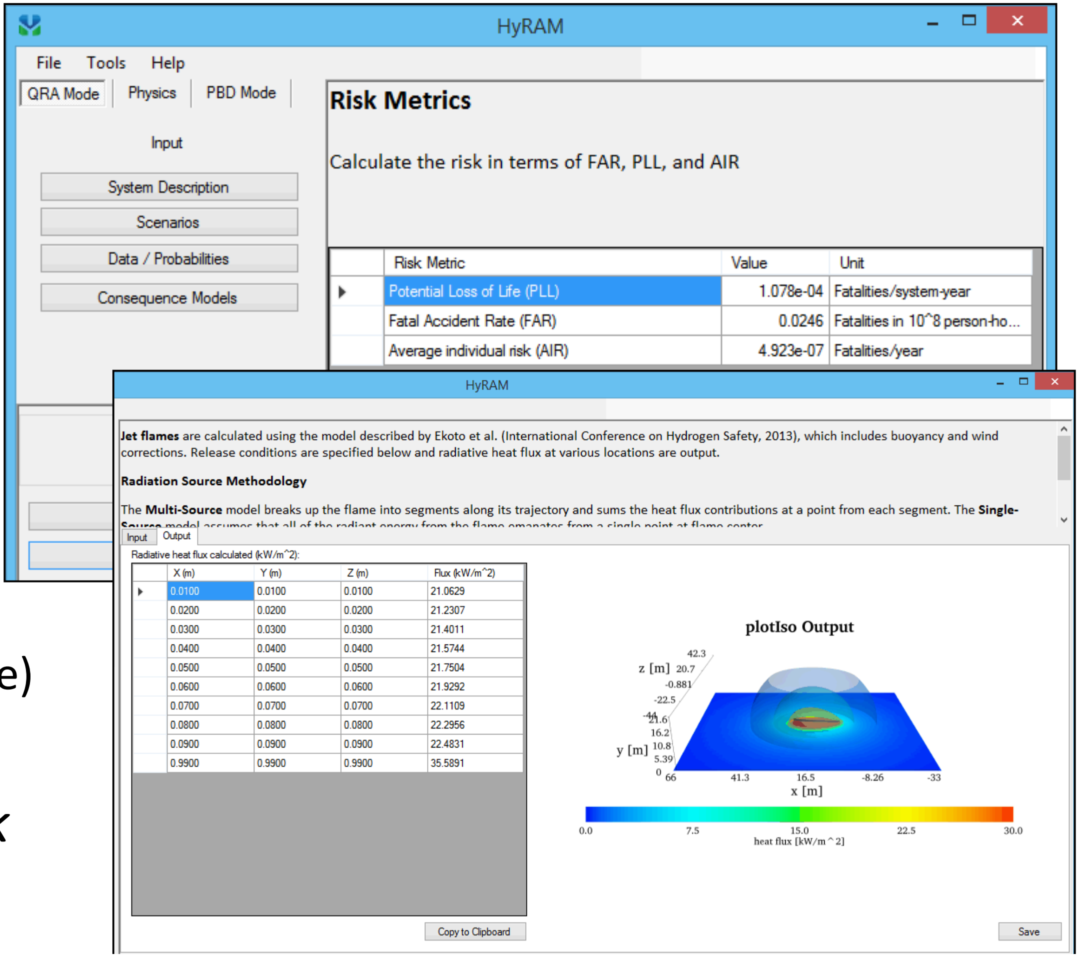
HyRAM in one slide

- **Integration platform** for state-of-the-art hydrogen safety models & data
  - Generic reliability data for H2 systems
  - Standardized scenarios and models
  - H2 phenomena (gas release, ignition, heat flux, overpressure)
- Software built to enable **industry-led** *quantitative risk assessments* (QRAs)
  - Puts the R&D into the hands of H2 industry safety experts



HyRAM
HYDROGEN RISK ASSESSMENT MODELS

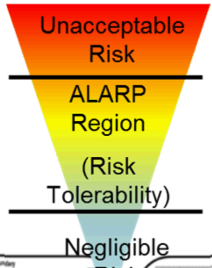
Motivation for HyRAM: *Enable QRA success*

Analysis Goal	Means
Completeness	Use comprehensive modeling tool
Comparability	Use standard, flexible modeling tool
Robustness	• Use validated models (as available), standardized models if you don't. • Update models as knowledge improves
Repeatability	Document the analysis
Verifiability	Establish a consistent benchmark for the hydrogen community

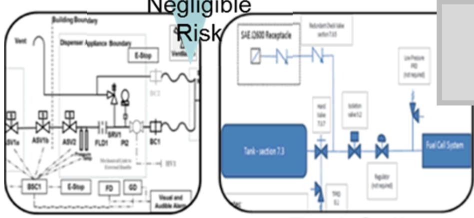
Motivates building a unifying framework

HyRAM
+
H2 R&D community

QRA Process & HyRAM philosophy

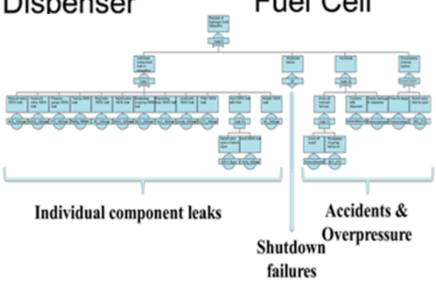


1. Set analysis goals

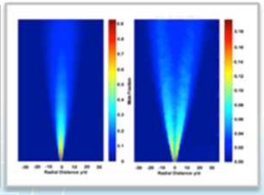


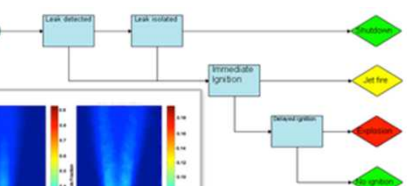
2. System & hazard description

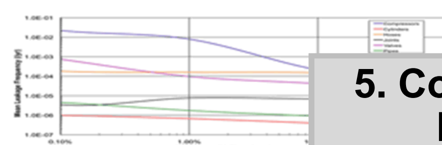
3. Cause analysis



4. Consequence analysis







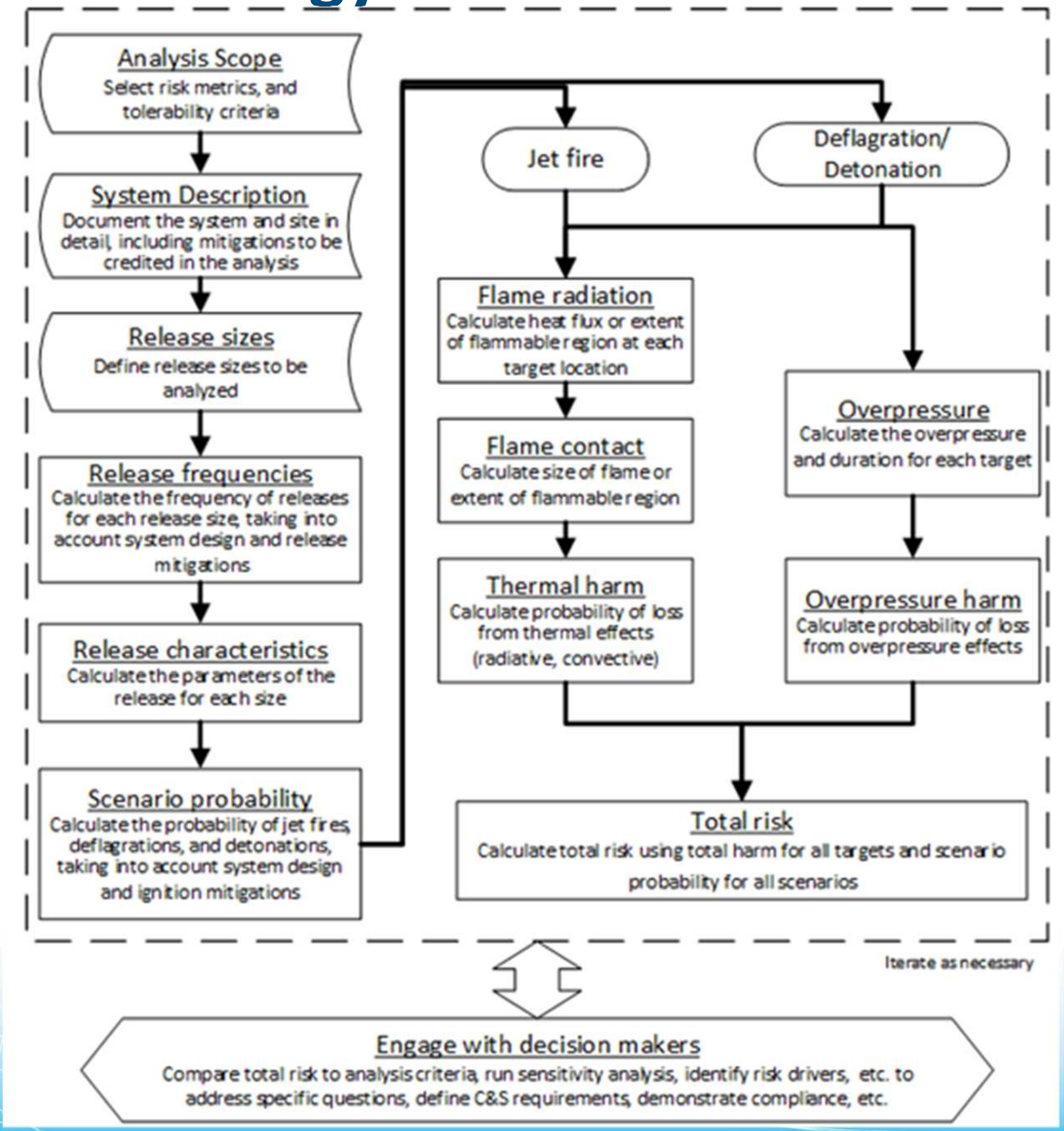
Occupation	FAR
U.S. Workforce total	1.8
Construction and extraction occupations	5.9
Industrial machinery, installation, repair, and maintenance workers	10.4
Industrial truck and tractor operators	3.0
Laborers and freight, stock, and material movers, hand	3.1
Farming, fishing, and forestry occupations	13.5

5. Communicate Results

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

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

HyRAM Methodology & Main elements



Major elements of HyRAM 1.0 algorithm

QRA Methodology

- Risk metrics calculations
- Scenario Models
- Frequency of a gaseous hydrogen release
- Consequence Models
  - Jet fire
  - Explosion (overpressure)
  - Harm & loss models

Generic freq. & prob. data

- Release Detection and Isolation Probability
- Ignition Probabilities
- Prob. of flash fire vs. explosion
- Component leak frequencies

Physics models

- Properties of Hydrogen
  - REFPROP & Abel-Noble equation sof state
- Unignited releases
  - Orifice flow
  - Notional nozzles
  - Gas jet/plume
  - Accumulation in confined areas /enclosures
- Ignited releases
  - Jet flame w/o buoyancy correction
  - Jet flame w/ buoyancy correction
  - Jet flame radiation
  - Overpressure in enclosures

Mathematics Middleware

- Unit Conversion System
- Math.NET Numerics

Recent progress & publications

HyRAM documentation

- KM Groth, ES Hecht & JT Reynolds. *Methodology for assessing the safety of Hydrogen Systems: HyRAM 1.0 technical reference manual.* SAND2015-DRAFT, ~Nov 2015.)
- KM Groth and ES Hecht. HyRAM: A methodology and toolkit for Quantitative Risk Assessment of Hydrogen Systems. ICHS 2015.
- HR Zumwalt and KM Groth. *HyRAM V1.0 User's Manual* .SAND2015-7380 R., Sandia National Laboratories, Albuquerque, NM August, 2015.

HyRAM applications (PBD)

- AC LaFleur, AB Muna, & KM Groth. *Fire Protection Engineering design Brief Template: Hydrogen Refueling Station,* SAND2015-4500, Sandia National Laboratories, June 2015.
- A. C. LaFleur, A. B. Muna and K. M. Groth "Application of Quantitative Risk Assessment for Performance-Based Permitting of Hydrogen Fueling Stations" ICHS 2015.

Experimental work:

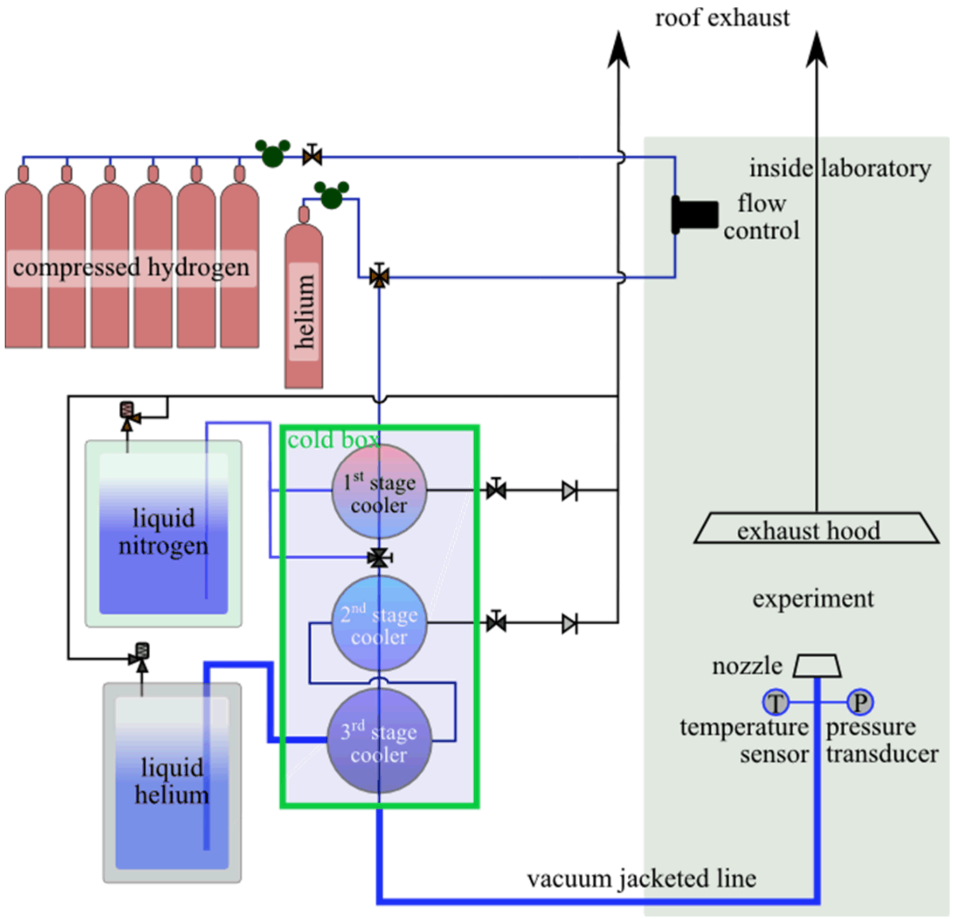
- ES Hecht, MD Zimmerman, AC LaFleur & M Ciotti. *Design of the Cryogenic Hydrogen Release Laboratory*. SAND2015-7521, September **2015**
- E. S. Hecht, X. Li and I. Ekoto. Validated equivalent source model for an underexpanded hydrogen jet. ICHS 2015.
  I.W Ekoto, E. Hecht, C. San Marchi, KM Groth, AC LaFleur, N. Natesan, M. Ciotti and A. Harris *Liquid Hydrogen Release and Behavior Modeling: State-of-the-Art Knowledge Gaps and Research Needs for Refueling Infrastructure Safety.* SAND2014-18776, October, 2014.

HyRAM updates since April (Demo in software)

- Overpressure model in physics mode – initial UI
- Reconfigured jet flame physics UI & added more variables for user inputs
- New UI for occupant/target positions in QRA mode
- New Master Input editor to improve usability
- Testing & validation activities
- Documentation
  - Technical reference manual
  - User manual

Cold Hydrogen Release Laboratory

- Goal: Build laboratory that can be used to develop validated model needed for QRA of release from cryogenic storage
  - Well controlled boundary conditions and accurate diagnostics necessary for proper model validation
- Components being fabricated and assembled
- Expected trials by then end of FY15



Next steps

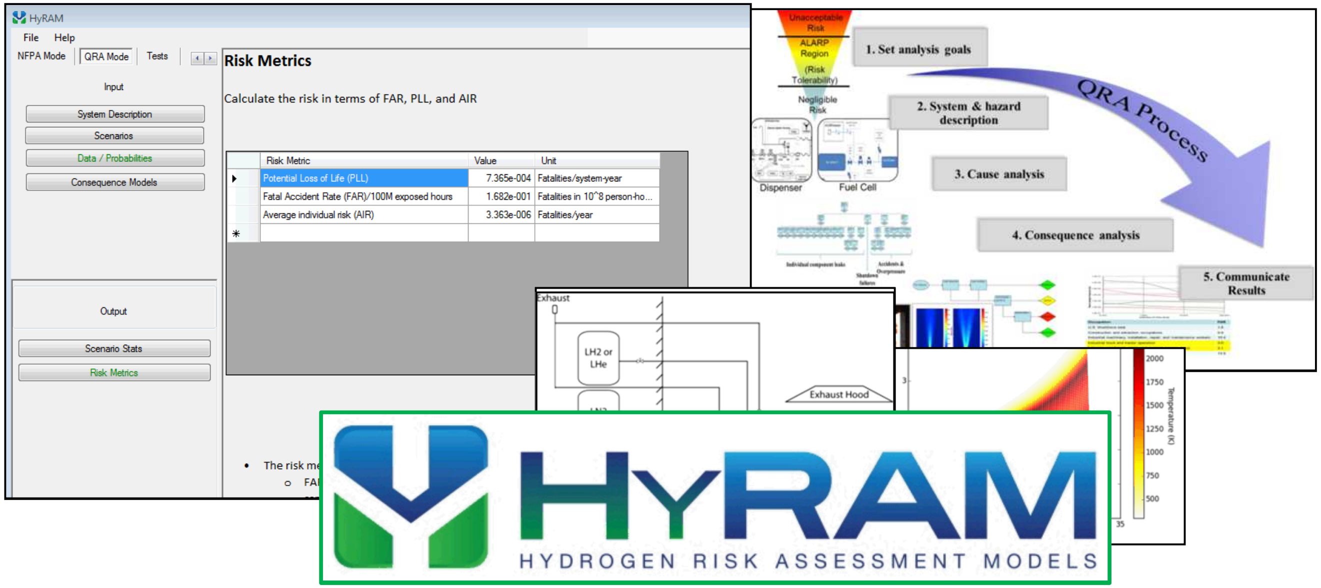
- Rest of 2015:
  - **HyRAM**: Integration of overpressure model into QRA mode; alpha user testing via main partners
  - **Behavior**: Develop experimental capability for liquid/cryogenic H_2 behavior (w/ financial support of industrial stakeholders)
- FY16:
  - **HyRAM**: Add risk-features (Fault Trees); public release of HyRAM 1.0.
  - **Behavior**: Conduct liquid/cryogenic H_2 release experiments and develop validated LH_2 release model
- Out-years
  - Highly accessible (web-based/app) tool for enabling end-users to implement these algorithms
  - Continue experimental work to generate needed validation data and develop necessary science-based models (e.g. wall interactions)

What else we need

- Partners for next phase – software development, testing
- CRADA participants -- Funding partners for cryo-lab & HyRAM development
- Published models, data, & programmed, licensable modules for QRA or physics…
  - Leak freq. data and component failure data for H2 components not yet in HyRAM
  - Ignition probability models
  - Deflagration (unconfined) and detonation
  - Flash fire
  - Impingement
  - Fault Tree/Event Sequence Diagrams
  - Uncertainty analysis
  - Flow/flame surface interaction

Group Discussion

- **Group discussion of the gaps in the toolkit and how the research from the community relates.**
- Where are there gaps?
- Who is working to fill them?
- What additional activities need to happen to align these pieces?



Thank you!

Katrina Groth

Sandia National Laboratories

kgroth@sandia.gov

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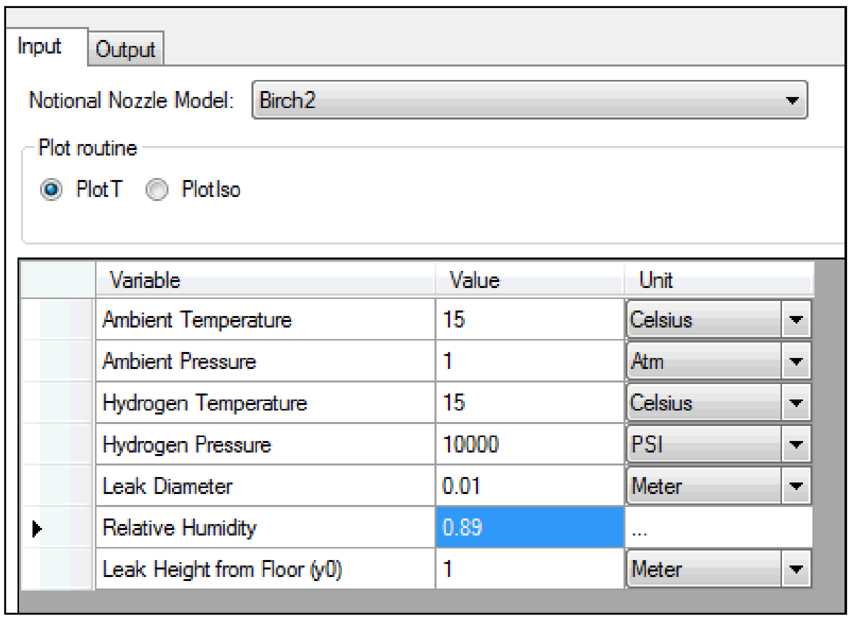
Example HyRAM calculation: Jet Flame physics

Consequence-only modeling

Input

- Leak size and known conditions.



Input | Output

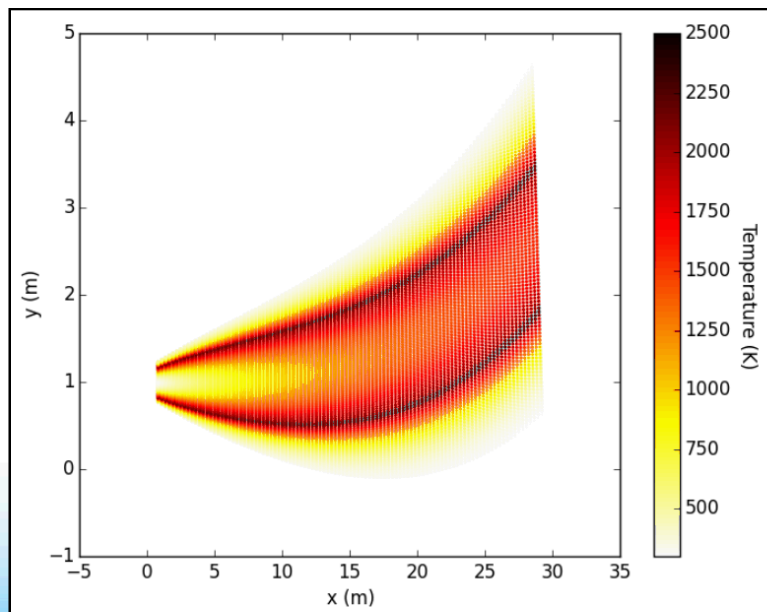
Notional Nozzle Model: Birch2

Plot routine: (•) PlotT ( ) PlotIso

Variable	Value	Unit
Ambient Temperature	15	Celsius
Ambient Pressure	1	Atm
Hydrogen Temperature	15	Celsius
Hydrogen Pressure	10000	PSI
Leak Diameter	0.01	Meter
Relative Humidity	0.89	...
Leak Height from Floor (y0)	1	Meter

Output

- Shows flame temperature at different distances -- direct analog to original safety distance work.

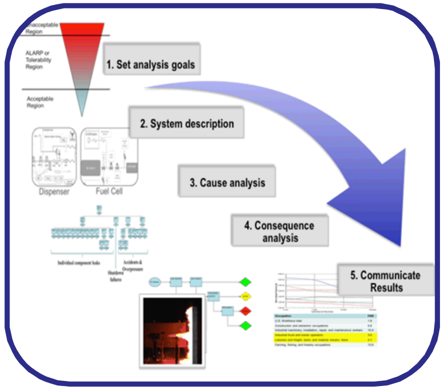


Project Approach: Three coordinated activities

Apply R&D in RCS

Apply risk assessment techniques in step-out hydrogen technologies

QRA methods, tools



Develop integrated algorithms for conducting QRA (Quantitative Risk Assessment) for H_2 facilities and vehicles

H2 behavior R&D

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

Enabling methods, data, tools for H2 safety & RCS community

Example HyRAM calculation: Full QRA

Allows credit for mitigations that reduce likelihood of events & provides system-specific risk-reduction insight

Input

- System description (components, parameters, facility description)

Components | System Parameters | Facility Parameters

Piping | Vehicles

Variable	Value	Unit
Pipe Outer Diameter	0.375	Inch
Pipe Wall Thickness	0.065	Inch
Internal Temperatu		
Internal Pressure		
External Temperatu		
External Pressure		

Components | System Parameters | Facility Parameters

Component	Count	Unit
# Compressors	0	...
# Cylinders	0	...
# Valves	5	...
# Instruments	3	...
# Joints	35	...
# Hoses	1	...

Facility | Occupants

Input Details | Distribution

Variable	Value
Population (Number of persons)	50
Working hours per year	2000

Output

- Total system risk
  - Enables comparisons, e.g. risk with vs. without gas detection

Risk Metric	Value	Unit
Potential Loss of Life (PLL)	4.500e-04	Fatalities/system-year
Fatal Accident Rate (FAR)/100M exposed hours	0.1027	Fatalities in 10^8 person-ho...
Average individual risk (AIR)	2.055e-06	Fatalities/year

Risk Metric	Value	Unit
Potential Loss of Life (PLL)	5.000e-04	Fatalities/system-year
Fatal Accident Rate (FAR)/100M exposed hours	0.1141	Fatalities in 10^8 person-ho...
Average individual risk (AIR)	2.283e-06	Fatalities/year

- Insight into risk drivers: scenario frequency & risk ranking

Scenario	End State Type	Avg. Events/Year	PLL Contribution
0.01pct Release	No Ignition	0.03448206	0.00%
0.1pct Release	No Ignition	0.00495318	0.00%
1pct Release	No Ignition	0.00148741	0.00%
10pct Release	No Ignition	0.00116683	0.00%
100pct Release	No Ignition	0.00071471	0.00%
0.01pct Release	Jet fire	0.00025097	0.00 %
0.01pct Release	Explosion	0.00012448	0.01 %
100pct Release	Jet fire	0.00003669	0.00 %
0.1pct Release	Jet fire	0.00003605	0.00 %
0.1pct Release	Explosion	0.00001788	0.00 %
100pct Release	Explosion	0.00001770	95.15 %
1pct Release	Jet fire	0.00001083	0.00 %
10pct Release	Jet fire	0.00000849	0.00 %
1pct Release	Explosion	0.00000537	0.03 %
10pct Release	Explosion	0.00000421	4.81 %