Sandia National Laboratories

H2FC Hydrogen and Fuel Cells Program

Quantitative Risk Analysis to Guide Station Design

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Sandia National Laboratories

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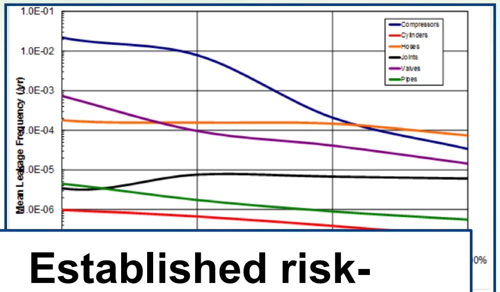
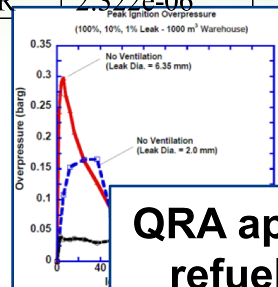
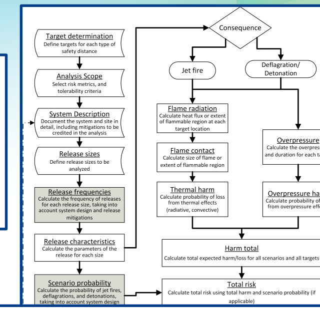
Quantitative Risk Assessment is enabling infrastructure deployment



PLL	5.084e-04
FAR	0.1161
AIR	2.322e-06





Established risk-informed processes for separation distances

QRA applied to indoor refueling to inform code revision

Performance-based system layout demonstrated

ISO TC197 WG24 incorporating QRA and behavior modeling

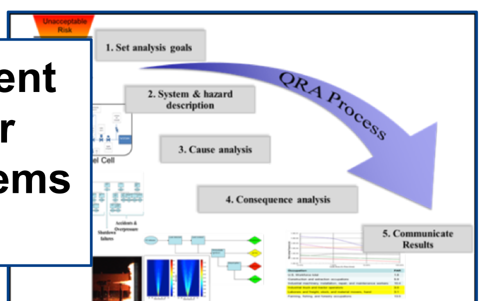
2005 — 2007 — 2009 — 2011 — 2013 — 2015 — 2017

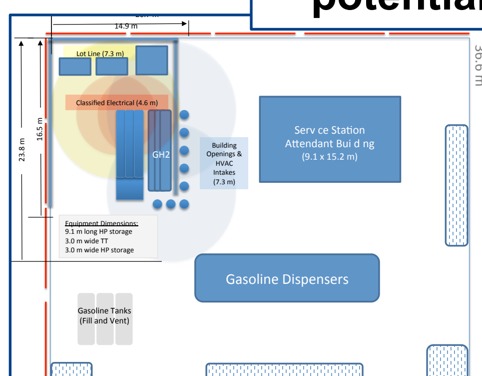
Risk assessment proposed for hydrogen systems at ICHS

QRA-informed separation distances in NFPA 2

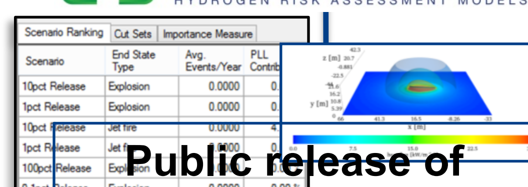
20% station penetration potential due to QRA

Public release of HyRAM R&D tool



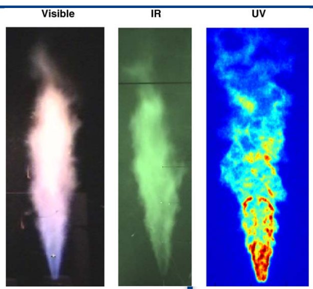


HYRAM
HYDROGEN RISK ASSESSMENT MODELS



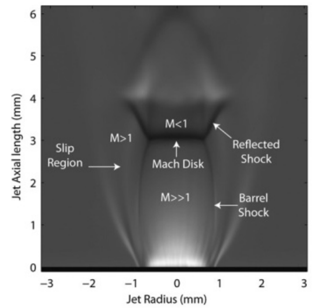
Hydrogen behavior studies are at the foundation of consequence modeling capabilities

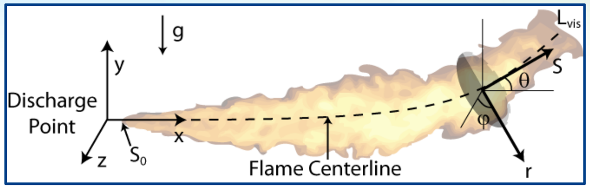
Radiative properties of H2 flames quantified



Barrier walls for risk reduction

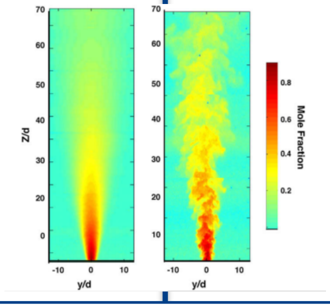
Ignition of under-expanded H2 jets





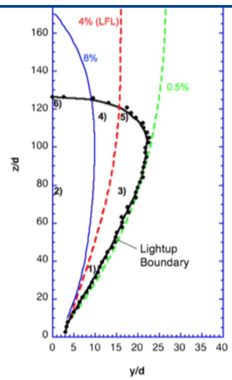
Buoyant jet flame model with multi-source radiation

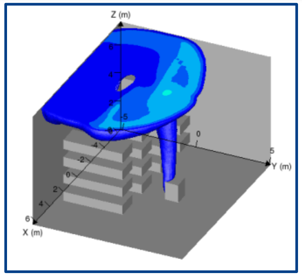
2005 2007 2009 2011 2013 2015 2017



Advanced laser diagnostics applied to turbulent H2 combustion

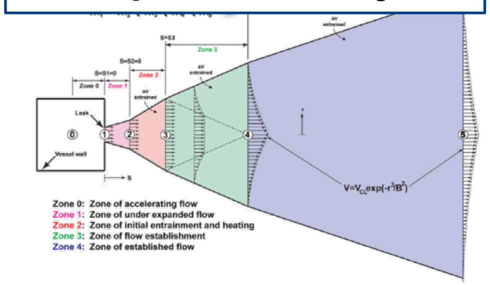
Ignition limits of turbulent H2 flows





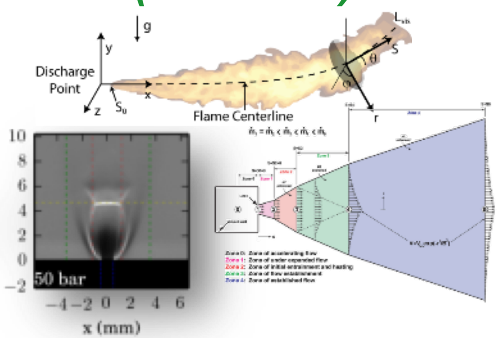
Experiment and simulation of indoor H2 releases

Laboratory-scale characterization of LH2 plumes and jets



Coordinated activities to enable consistent, rigorous, and accepted safety analysis

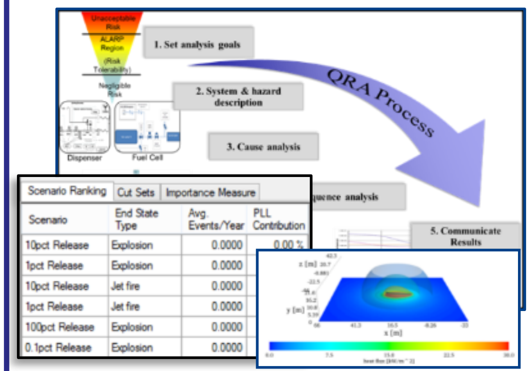
Behavior R&D (SCS 010)



Develop and validate scientific models

to accurately predict hazards and harm from liquid releases, flames, etc.

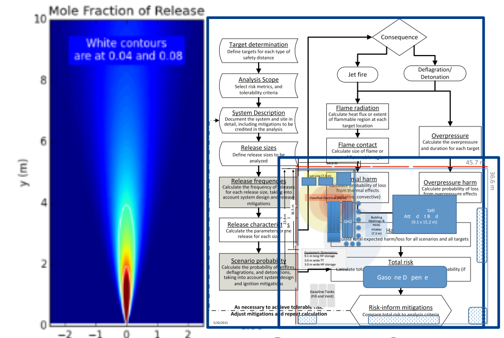
Risk R&D (SCS 011)



Develop integrated methods and algorithms

for enabling consistent, traceable and rigorous QRA

Application in SCS (SCS025)

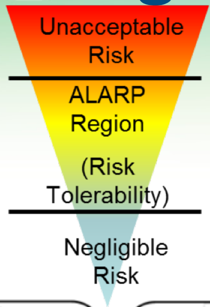


Apply QRA & behavior models to real problems

in hydrogen infrastructure and emerging technology

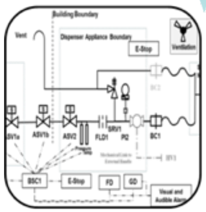
Developing methods, data, tools for H_2 safety & SCS

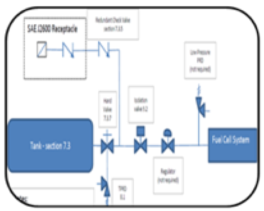
Building a Scientific Platform for Hydrogen QRA



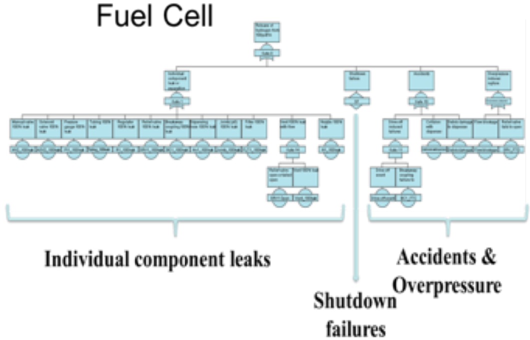
1. Set analysis goals

QRA Process


Dispenser

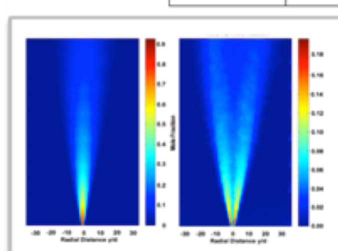

Fuel Cell

2. System & hazard description



3. Cause analysis

4. Consequence analysis



5. Communicate Results

Challenge: A quality QRA incorporates a large body of information from different areas

- QRA data
  - Relevant hazards
  - Exposure scenarios
  - Gas data
    - Chemical properties
  - System data
    - Component counts
    - Component configuration
  - Facility data
    - Warehouse configuration
    - Population data (human)
    - Population data (fuel cells)
  - Frequency data
    - Release occurrence
      - Component failures
      - Human errors
      - Accidents
    - Ignition occurrence
    - Mitigating event occurrence
  - Consequence data
    - H2 release behavior
    - H2 dispersion behavior
    - H2 accumulation behavior
    - Fire [load] models
      - Jet flames
    - Explosion/ deflagration [load] models
  - Loss / harm data
    - Thermal effects
    - Overpressure effects
    - Toxicity effects

It is necessary to…

- Find best-available models & data for all of these pieces
- Validate those models
- And combine all into a single framework

HyRAM: Making hydrogen safety science accessible through integrated tools

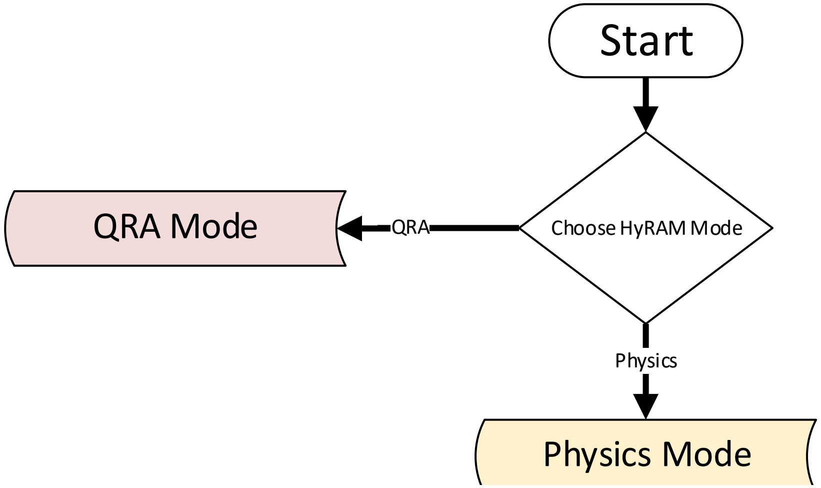
First-of-its-kind integration platform for state-of-the-art hydrogen safety models & data - **built to put the R&D into the hands of industry safety experts**

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 1.1.1.1341

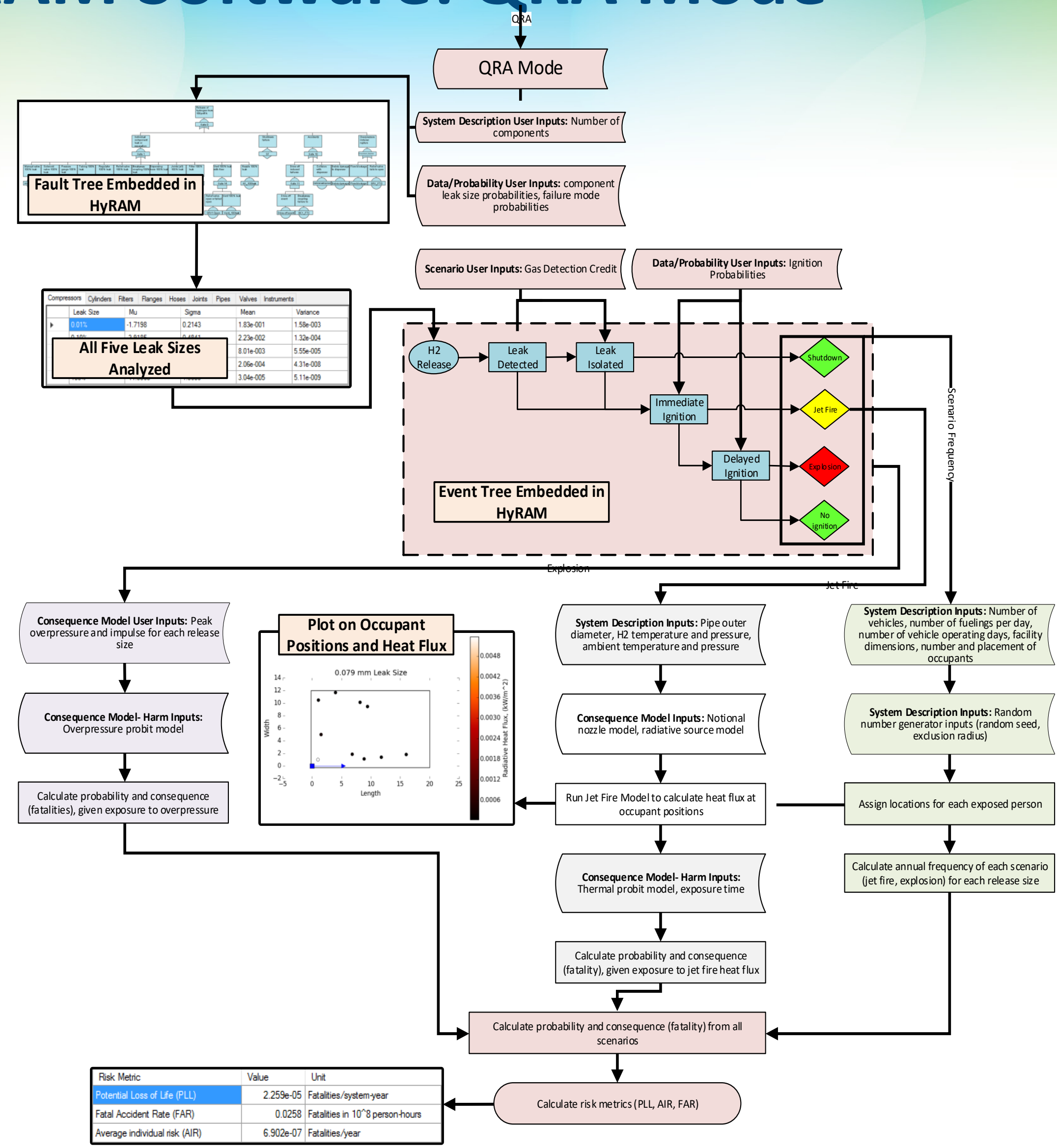
Major Elements of HyRAM Software: QRA Mode

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)

Software Language
- C# for GUI and QRA (planned conversion of QRA to Python)
- Python for Physics Modules

Documentation
- Algorithm report (SAND2017-2998)
- User guide (SAND2018-0749)



Major Elements of HyRAM Software: Physics Mode

Physics models

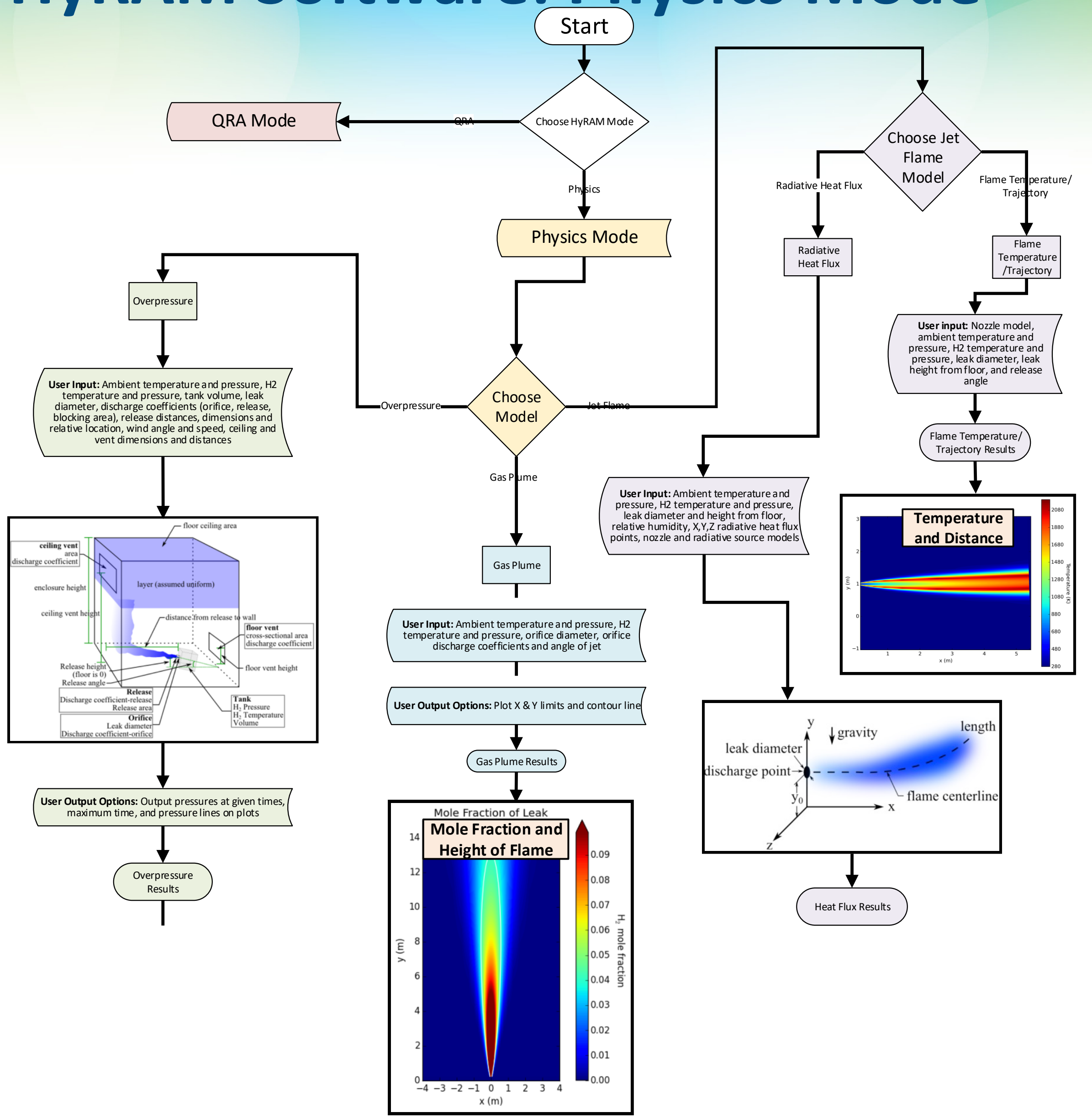
- Properties of Hydrogen
- Unignited releases: Orifice flow; Notional nozzles; Gas jet/plume; Accumulation in enclosures
- Ignited releases: Jet flames; overpressures in enclosures

Software Language

- Python for Modules
- C# for GUI

Documentation

- Algorithm report (SAND2017-2998)
- User guide (SAND2018-0749)



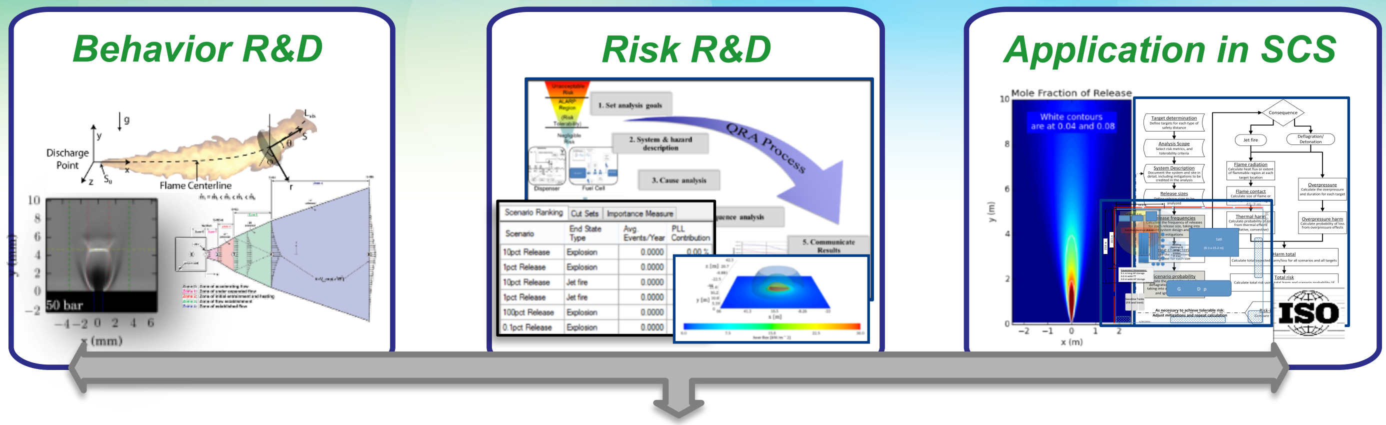
Summary

- **HyRAM is an integration platform built to enable hydrogen safety** for state-of-the-art H_2 safety models – enables consistent industry-led QRA and consequence analysis with documented, referenceable, validated models

- **Demonstrated Impact:** Enabling the deployment of refueling stations by developing science-based, risk-informed codes & standards
  - Analyses for NFPA 2 and ISO TR-19880-1
  - Benchmarked results (SAND2014-3416): Survey of proposed H2 stations show that changes to NFPA 2 gaseous separation distance requirements increased station siting options by 20%.

Sandia National Laboratories

H_2FC Hydrogen and Fuel Cells Program



HyRAM
HYDROGEN RISK ASSESSMENT MODELS

Thank you!

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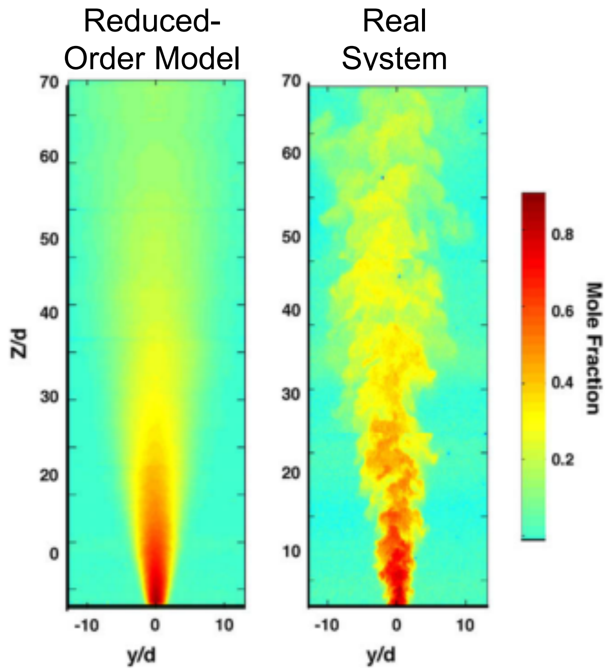
https://hyram.sandia.gov

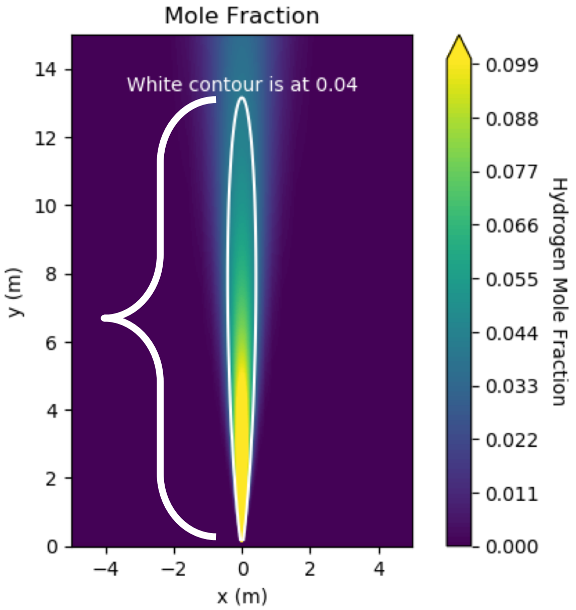
Research supported by DOE Fuel Cell Technologies Office (DOE EERE/FCTO)

Technical Back-Up Slides

Benefits of Reduced-Order Models

- Short run-time
- Modeling expert not required
- Useful for quantification
  - If a hydrogen leak occurs, how far away does the hazard get?
- Useful for comparisons
  - What is the effect on safety is a system size is reduced?



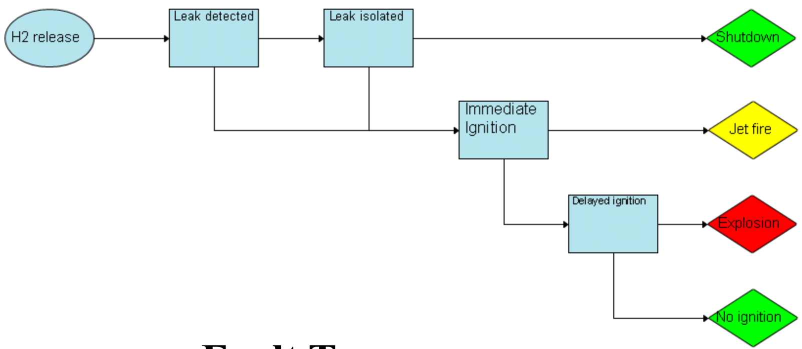


Greater Fidelity and Flexibility of QRA Models

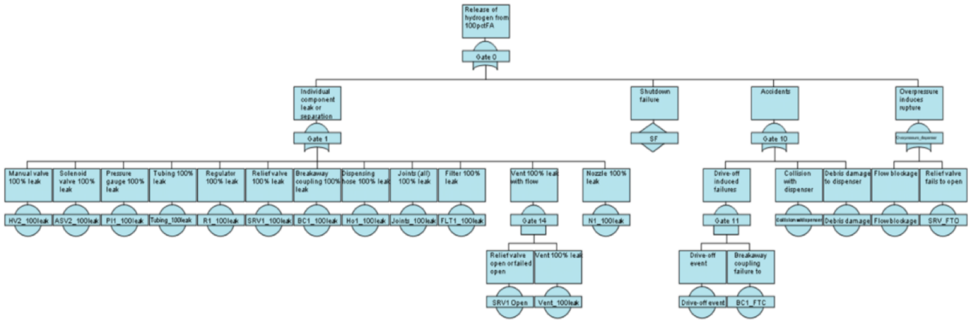
Expand HyRAM QRA beyond fueling stations

- **Customization of event and fault trees**
- Perform risk assessment and **calculate risk results in an efficient** manner
- Applicable for new hydrogen industries **beyond fueling stations**
- Underlying physics-based analysis would remain the same

Event Sequence Diagram



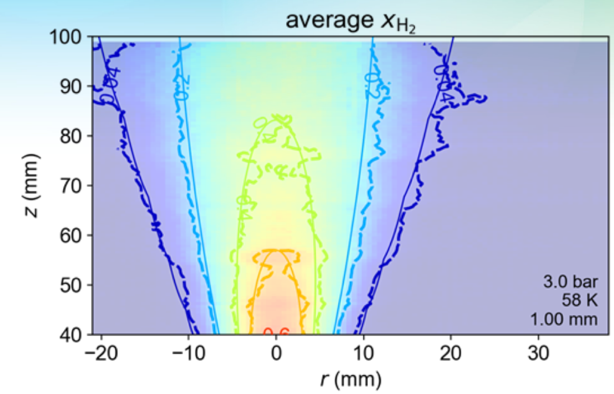
Fault Trees

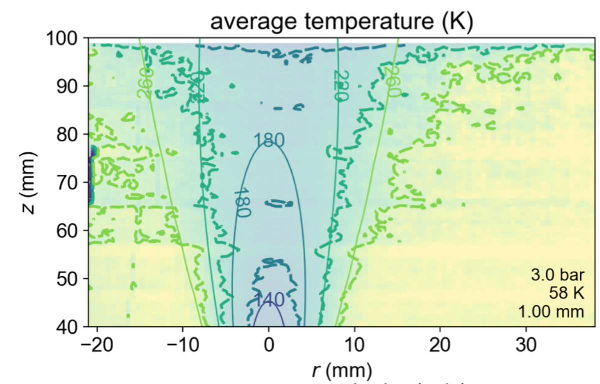


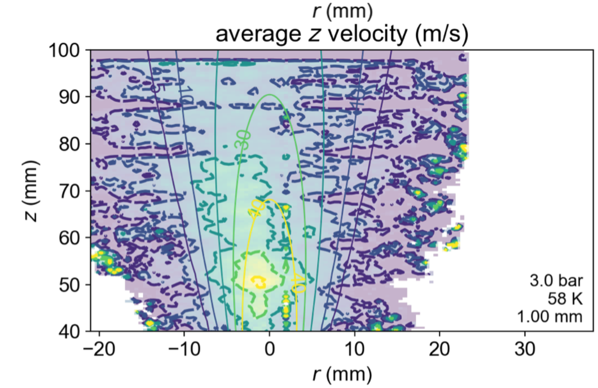
Customization of scenario will lead to broader application of HyRAM and hydrogen QRA

Laboratory-scale characterization of LH2 plumes and jets

- Validation of near-field model complete including mole fraction, temperature and velocity
- Development of diagnostic to measure full-scale cold vapor releases underway
- Development of full-scale release experiments underway





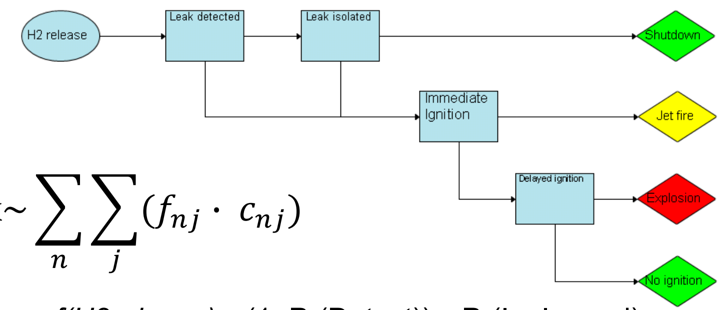


Validated LH2 release model will be used to risk-inform the revised LH2 bulk separation

R&D provides science-based tools: Examples of *Scenario & Probability* models

Accident sequences

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



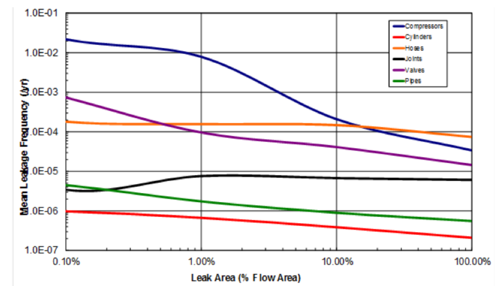
$$\text{Risk} \sim \sum_{n} \sum_{j} (f_{nj} \cdot c_{nj})$$

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

Release frequency

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

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



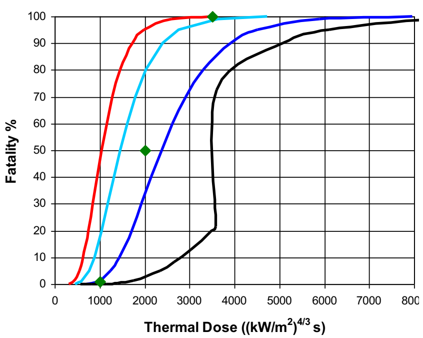
Ignition probability

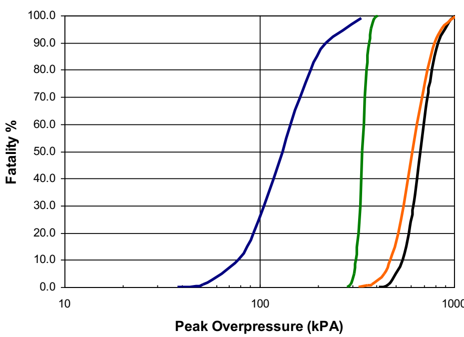
- Extrapolated from methane ignition probabilities
- Flow rate calculated using *Release Characteristics* module

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

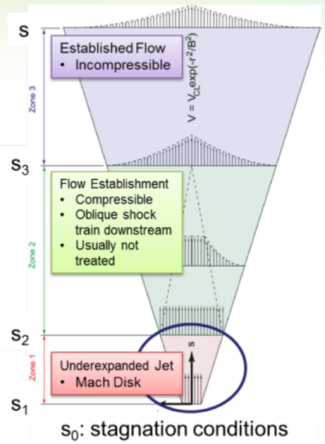


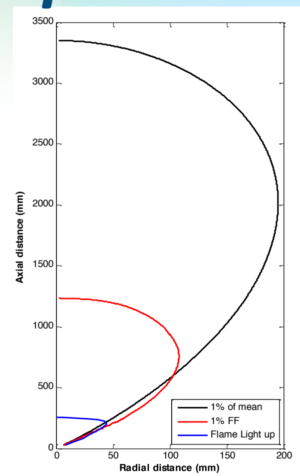


R&D provides science-based tools: Examples of *Behavior & Consequence models*

Release Characteristics

- Prediction of hydrogen jet plumes (concentration boundaries)
- Prediction of hydrogen jet flames
- Simplified models of hydrogen sources (choked flow, notional nozzles, etc)



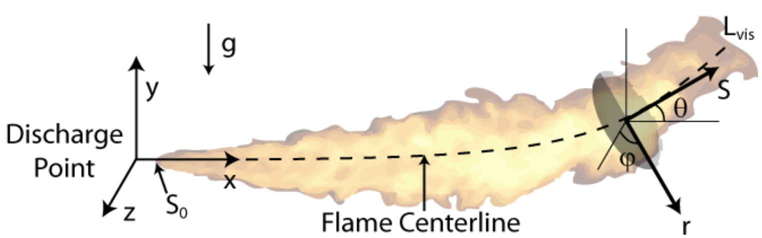


Ignition/Flame Light-up

- Prediction of ignition (flammability factor concept)
- Identification of light-up boundaries
- Prediction of sustained flame

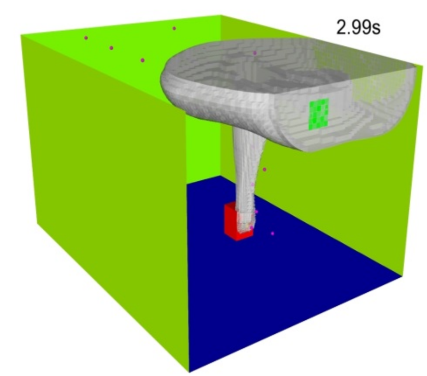
Flame Radiation

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



Deflagration within Enclosures

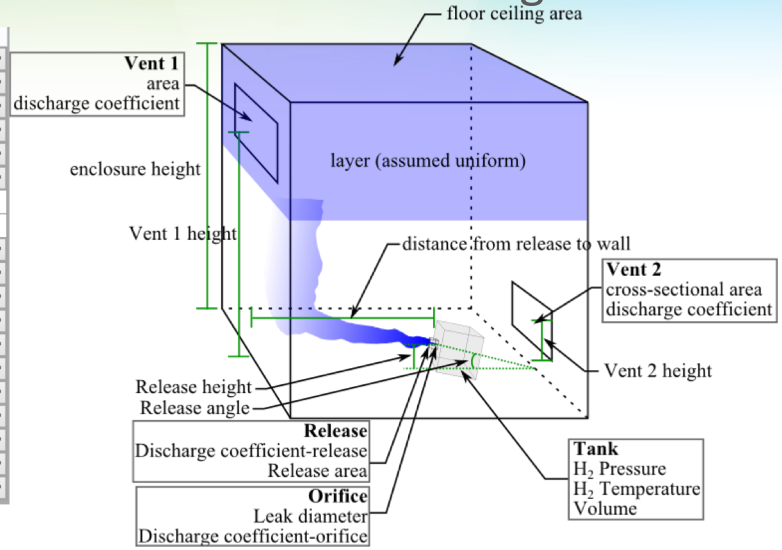
- Overpressure associated with deflagration
- Quantitative role of ventilation



Overpressure & layer modules

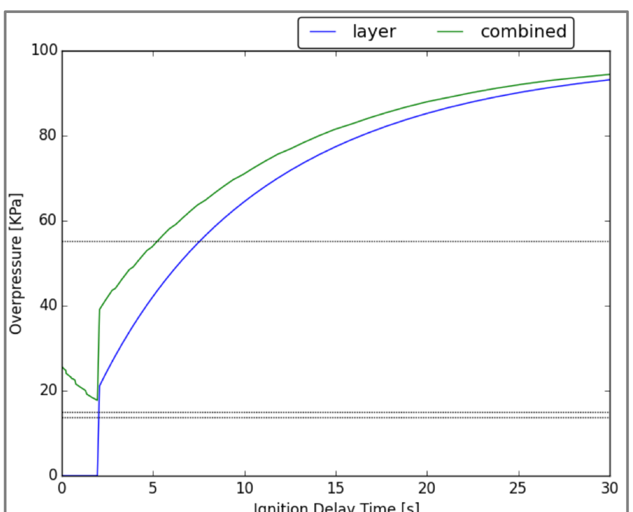
Input: Release conditions and enclosure configuration

Variable	Value	Unit
Ambient Pressure	101325	Pa
Ambient Temperature	288.15	Kelvin
H2 Tank Pressure	70	MPa
H2 Tank Temperature	287.8	Kelvin
H2 Tank Volume	0.00363	CubicMeter
Leak Diameter	0.1	Centimeter
Discharge Coefficient-Orifice	0.61	...
Discharge Coefficient-Release	1	...
Release Area	0.01716	SqMeters
Release Height	0.2495	Meter
Enclosure Height	2.72	Meter
Floor/Ceiling Area	16.72216	SqMeters
Distance from Release to Wall	2.1255	Meter
Vent 1 Cross-Sectional Area	0.090792027688...	SqMeters
Vent 1 Vent Height from Floor	2.42	Meter
Vent 2 Cross-Sectional Area	0.00762	SqMeters
Vent 2 Height from Floor	0.044	Meter
Vent Volumetric Flow Rate	0	CubicMeters...
Angle of Release (0=Horz.)	0	Degrees



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

Output: Overpressure (ignited) & Height of accumulated layer (unignited)

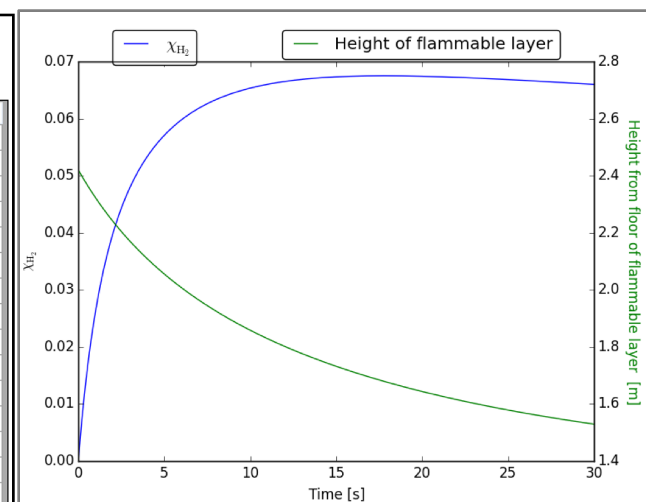


Maximum pressure (Pa): 94418.2835711473

Time this occurred (seconds): 30

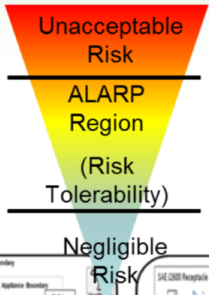
Time	Pressure
1	2.089E+004
2	2.670E+004
3	4.446E+004
4	4.957E+004
5	5.409E+004
6	5.841E+004
7	6.210E+004
8	6.528E+004
9	6.849E+004
10	7.105E+004
11	7.365E+004
12	7.595E+004
13	7.788E+004
14	7.982E+004
15	8.155E+004

Depth	Concentration
0.39711803	2.622E-002
0.47903418	3.974E-002
0.54935446	4.791E-002
0.61057559	5.331E-002
0.66450595	5.707E-002
0.71242342	5.979E-002
0.75545507	6.181E-002
0.79417555	6.332E-002
0.82938139	6.447E-002
0.86156604	6.535E-002
0.89098494	6.601E-002
0.91810608	6.651E-002
0.94312791	6.688E-002
0.96641626	6.714E-002
0.98800216	6.733E-002

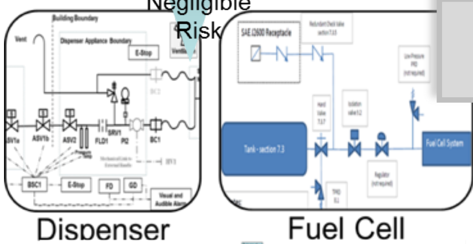


Building a scientific platform for hydrogen QRA

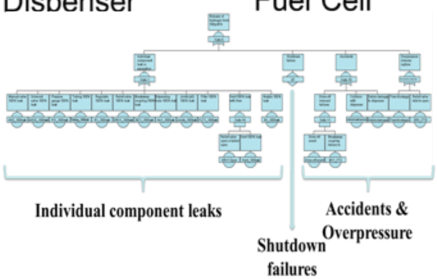
Adding more flexibility for users



1. Set analysis goals

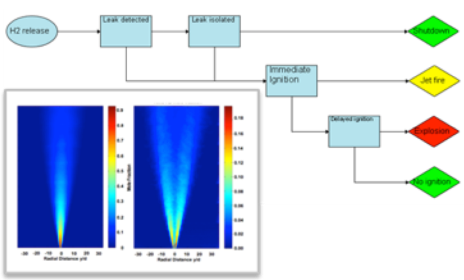


2. System & hazard description

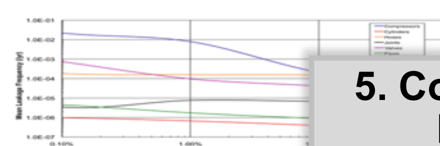


3. Cause analysis

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

User-specific – Elicit from range of stakeholders.

User-neutral – Establish science & engineering basis (with user input)