U.S. DEPARTMENT OF ENERGY
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HyRAM
HYDROGEN RISK ASSESSMENT MODELS

Hydrogen Risk Assessment Models 2.0: Open-source quantitative risk assessment framework

Brian D. Ehrhart, Ethan S. Hecht, Alice B. Muna, and Chris B. LaFleur, Sandia National Laboratory

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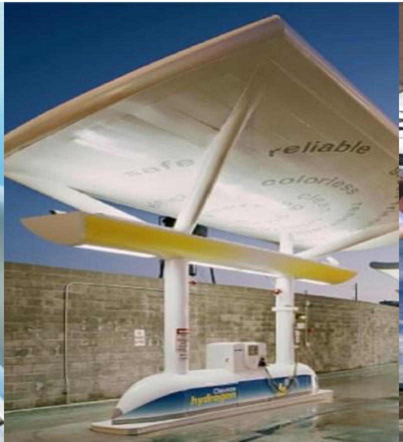
Fuel Cell Technologies Office Webinar
January 28, 2020

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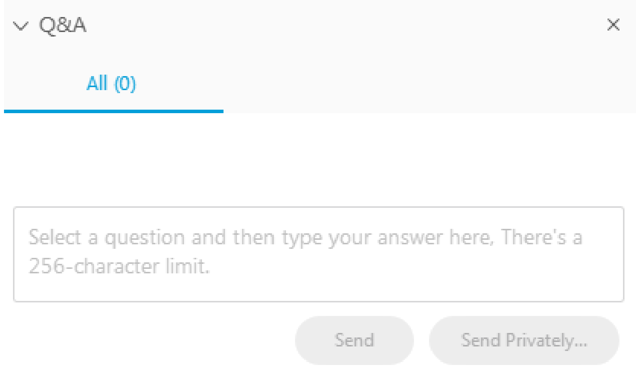

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Authorities look to NFPA 2 for standards on how to site hydrogen fueling stations

Prescribed separation distances:

- Different distances for different exposures
- Some distances able to be reduced with mitigations
- Justification for some (gaseous) separation distances provided in annex
  - ✓ Separation distance reductions in NFPA 2 2011 and again in 2020 enabled by Sandia-led scientific analyses

Or alternative means and measures:

- Demonstrate acceptable protections and risk for non-compliance to prescribed separation distance(s) to authority having jurisdiction (AHJ)
- Typically: all requirements can be met except a few

Or full performance-based design:

- Simulate all required design scenarios in NFPA 2 Chapter 5
- Typically: non-standard designs

2–42 HYDROGEN TECHNOLOGIES CODE

Table 7.3.2.3.1.1(a) Minimum Distance (D) from Outdoor [GH_2] Systems to Exposures — Typical Maximum Pipe Size

Pressure	>15 to ≤250 psig		>250 to ≤3000 psig		>3000 to ≤7500 psig		>7500 to ≤15000 psig	
Internal Pipe Diameter (ID) d_{mm}	>103.4 to ≤1724 kPa $d = 52.5_{mm}$		>1724 to ≤20,684 kPa $d = 18.97_{mm}$		>20,684 to ≤51,711 kPa $d = 7.31_{mm}$		>51,711 to ≤103,421 kPa $d = 7.16_{mm}$	
Group 1 Exposures	m	ft	m	ft	m	ft	m	ft
(a) Lot lines (b) Air intakes (HVAC, compressors, other) (c) Operable openings in buildings and structures (d) Ignition sources such as open flames and welding	12	40	14	46	9	29	10	34
Group 2 Exposures	m	ft	m	ft	m	ft	m	ft
(a) Exposed persons other than those servicing the system (b) Parked cars	6	20	7	24	4	13	5	16
Group 3 Exposures	m	ft	m	ft	m	ft	m	ft
(a) Buildings of noncombustible non-fire-rated construction	5	17	6	19	4	12	4	14
(b) Buildings of combustible construction								

2–58 HYDROGEN TECHNOLOGIES CODE

Table 8.3.2.3.1.6(A) Minimum Distance from Bulk Liquefied Hydrogen [LH_2] Systems to Exposures

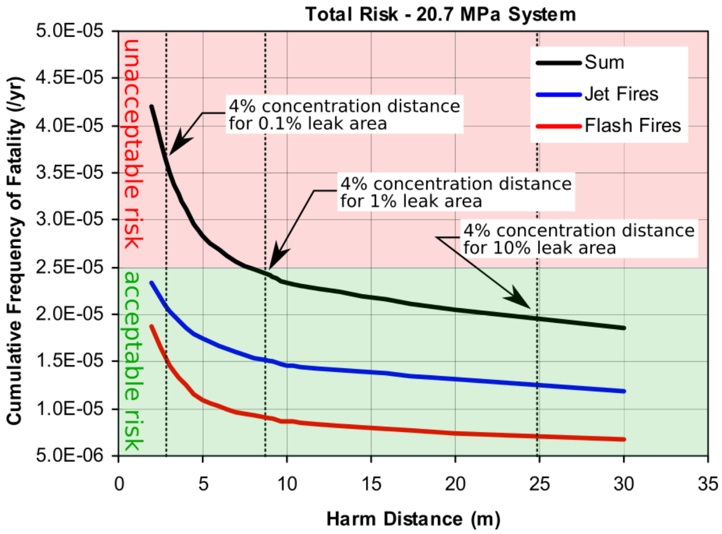
	Total Bulk Liquefied Hydrogen [LH_2] Storage					
	39.7 gal to 3500 gal	150 L to 13,250 L	3501 gal to 15,000 gal	13,251 L to 56,781 L	15,001 gal to 75,000 gal	56,782 L to 283,906 L
Type of Exposure	ft	m	ft	m	ft	m
Group 1						
1. Lot lines	25	7.6	50	15	75	23
2. Air intakes [heating, ventilating, or air conditioning equipment (HVAC, compressors, other]	75	23	75	23	75	23
3. Wall openings						
Operable openings in buildings and structures	75	23	75	23	75	23
4. Ignition sources such as open flames and welding	50	15	50	15	50	15
Group 2						
5. Places of public assembly	75	23	75	23	75	23
6. Parked cars (distance shall be measured from the container fill connection)	25	7.6	25	7.6	25	7.6
Group 3						
7. Building or structure						
(a) Buildings constructed of noncombustible or limited-combustible materials						
(1) Sprinklered building or structure or unsprinklered building or structure having	5[a]	1.5	5[a]	1.5	5[a]	1.5

Risk Assessment Concept

- **Risk** takes both **likelihood** and **consequence** into account
- **Likelihood** measures how often or how probable an event is
  - Frequency (events per year)
  - Probability
- **Consequence** measures the effects of some event occurring
  - Heat flux or overpressure
  - Fatalities/injuries
  - Economic losses
- Event with the highest risk may not be the most likely and it may not be the worst-case outcome
  - Combination of the two

Risk can be used to inform siting decisions (AM&M) and/or separation distances

- Overall **risk** assessment for siting/codes
  - Assume a representative facility
  - Assess the fatality risk of that facility
  - Compare risk to existing/equivalent hazardous activity
    - e.g., 2 x 10^{-5}/yr risk at gasoline station
- Leak **frequencies** determine leak size of interest
  - 1-10% of pipe area estimated to include 97-98% of all leaks
  - 3% pipe area used for 2011 Ed., 1% for 2020 Ed.
- H_2 **behavior** models to estimate effect of leak
  - Jet flame determines heat flux at distances away from leak
  - Harm criteria to determine distance for setback
  - 2011 Ed. assumed no-harm criteria with no mitigation
  - 2020 Ed. assumes bystander could move away



Modified version of plot from SAND2009-0874

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**

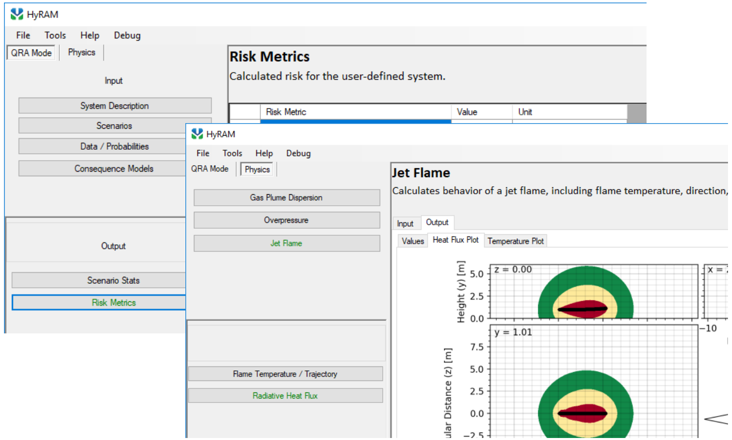
Core functionality:

- 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

HYRAM
HYDROGEN RISK ASSESSMENT MODELS



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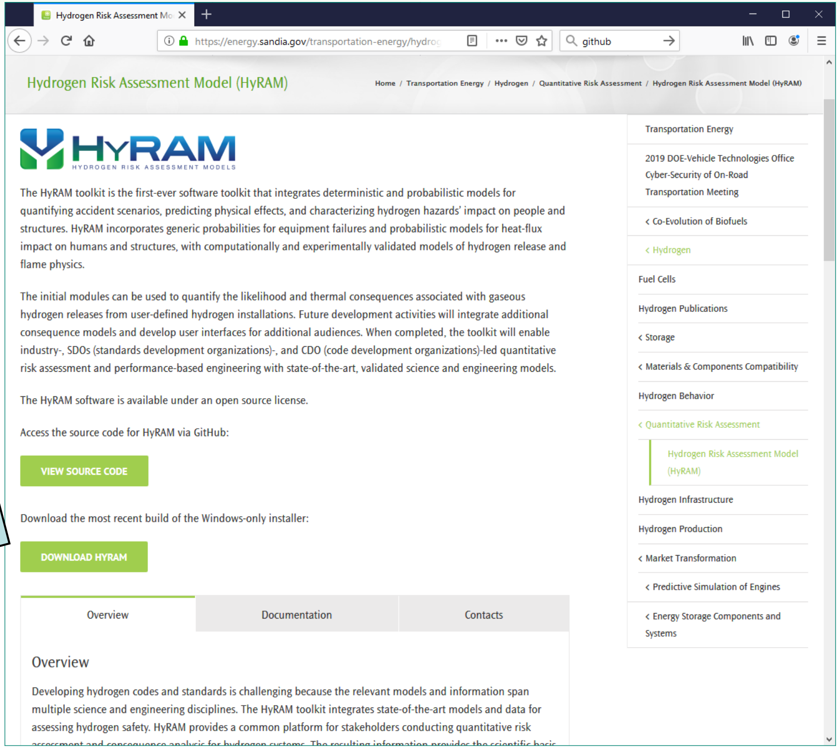
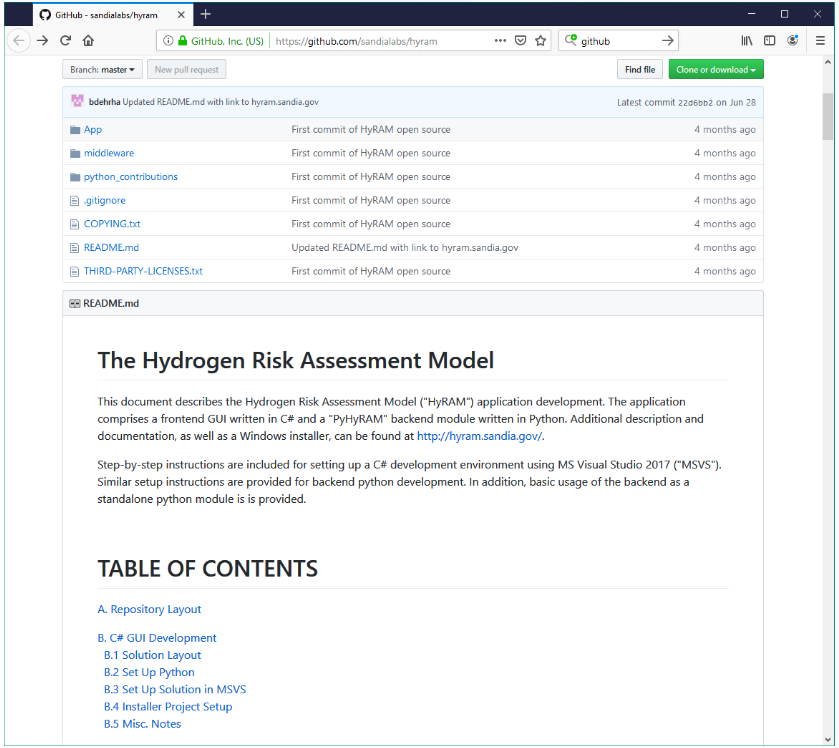
H2FC Hydrogen and Fuel Cells Program

HyRAM 2.0 can be installed as a Windows executable and as an open-source software, users have access to the source code



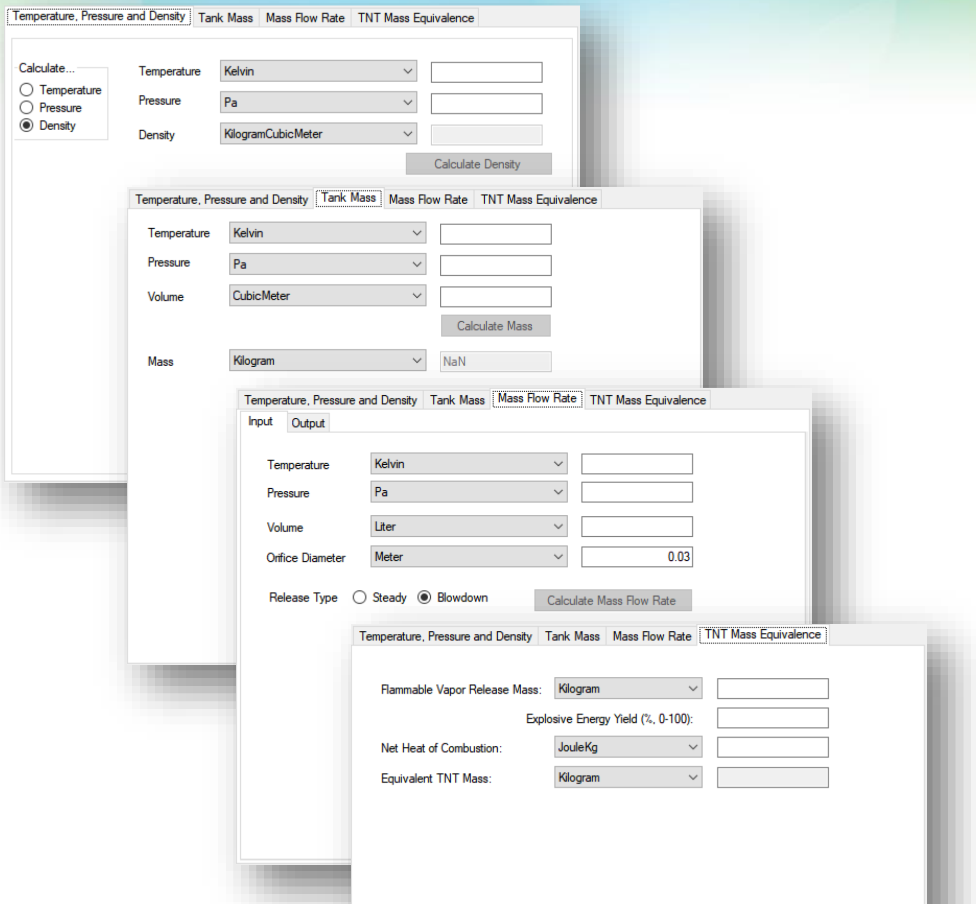


hyram.sandia.gov

github.com/sandialabs/hyram

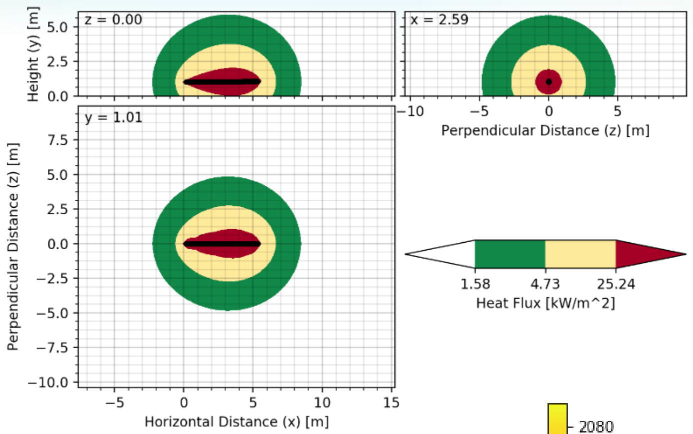
HyRAM GUI contains an Engineering Toolkit for common calculations

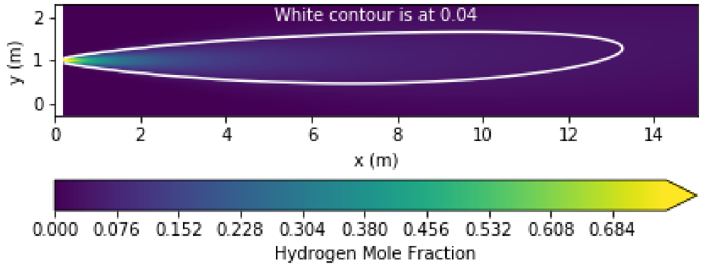
- Equation of state (density, *T*, *P*)
- Tank mass
- Mass flow rate (blowdown)
- TNT mass equivalence
- Valid for high pressures and near-ambient temperatures
  - Soon to be updated for cryogenic temperatures

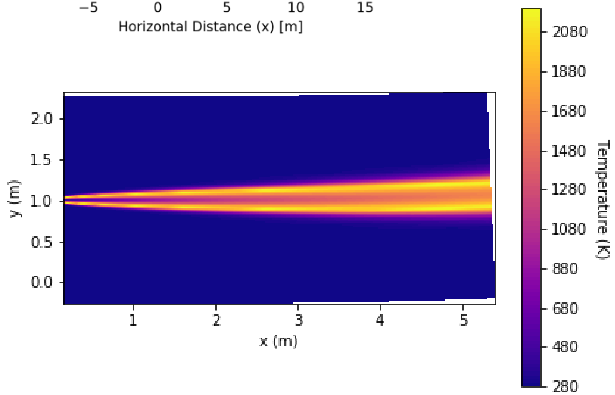


A variety of validated physical models are used in HyRAM, which can be used independently from QRA

- Unignited dispersion
  - Distance to certain concentration
- Flame model
  - Temperature field
  - Heat flux field
- Overpressure for delayed ignition of indoor releases

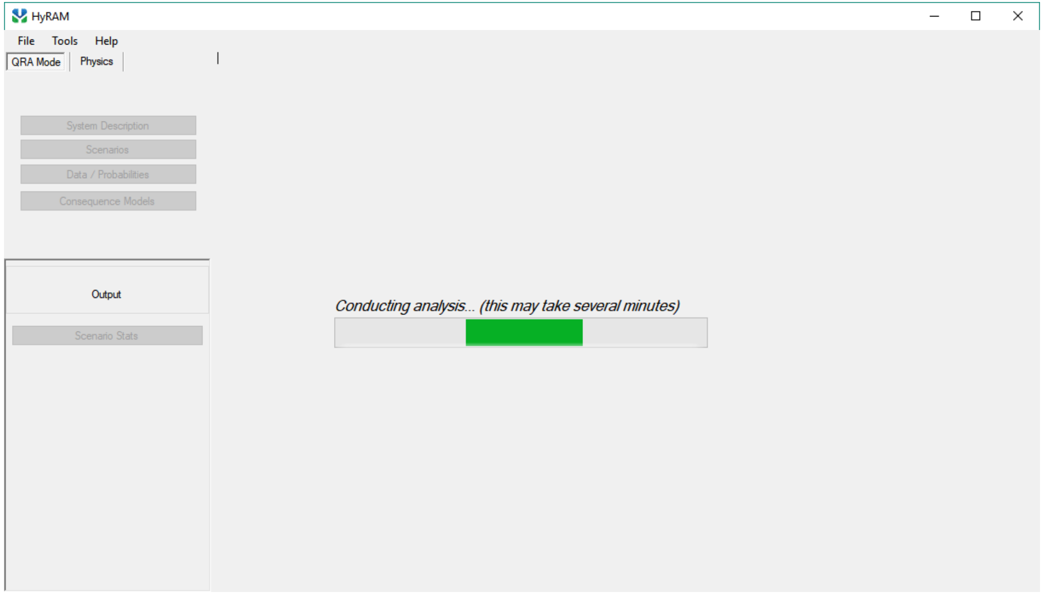






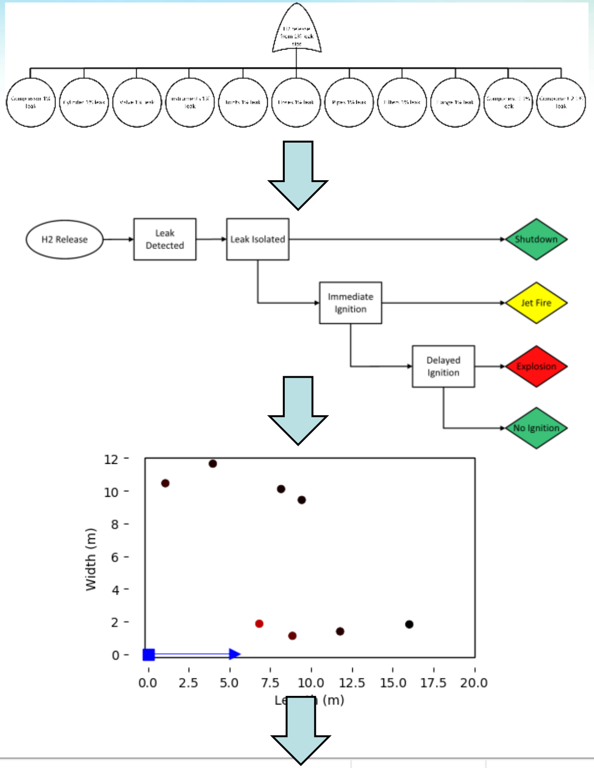
HyRAM 2.0 enables consistent, traceable, and rigorous QRA for specific systems

- ✓ User inputs system description
  - ✓ Number of components
  - ✓ Pressure
  - ✓ Nominal pipe size
- ✓ Generic probabilities an be updated if data is available
- ✓ Consequence models can be selected
- ➢ Risk metrics calculated
- ➢ Analysis can be saved



QRA estimates frequency and consequence for different leak sizes

- Frequency of Leak
  - 0.01%, 0.1%, 1%, 10%, 100%
- Probability of Outcome
  - Shutdown, jet fire, explosion, no ignition
- Calculate Harm
  - E.g., thermal heat flux to occupant
- Estimate Fatalities
  - Probability based on harm
- Risk Metrics
  - 20 Scenarios

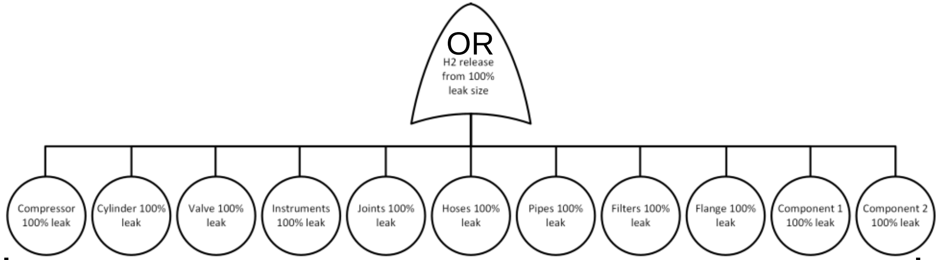


Risk Metric	Value	Unit
Potential Loss of Life (PLL)	1.246E-005	Fatalities/system-year
Fatal Accident Rate (FAR)	1.580E-002	Fatalities in 10^8 person-hours
Average individual risk (AIR)	3.160E-007	Fatalities/year

Leak Frequencies Determined with Fault Trees and Component Data

OR

OR



OR

AND

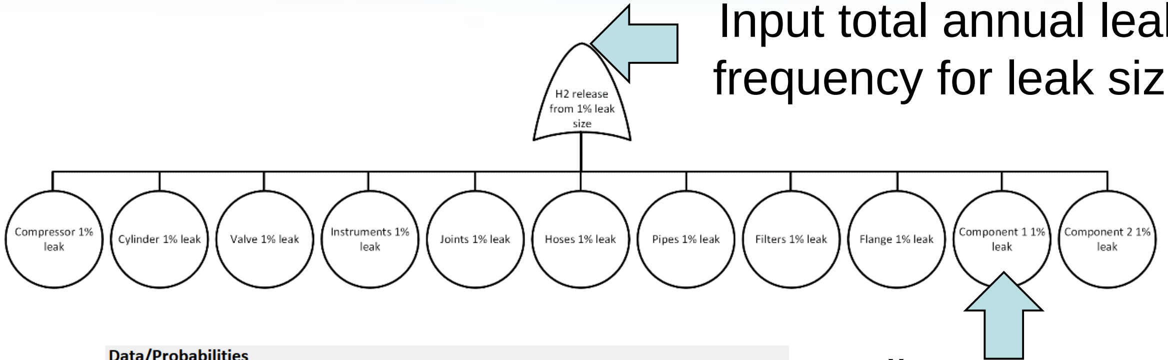
Individual component leak frequencies
(multiplied by number of components)

Fueling dispenser failure
(multiplied by number of fueling demands)
100% leak only

Model enables more flexible QRA

- Users can edit parameters of existing fault tree or substitute their user-defined results
  - Could come from external fault tree software
  - Could be due to historical system performance
- Updated HyRAM methodology enables users to alter the risk analysis for different applications

Input total annual leak frequency for leak size



Edit component leak frequencies

Data/Probabilities

Probability data quantifying the events contained in the scenario models (ESDs and FTs)

Component Leaks | Component Failures | Ignition Probabilities | Distributions

Accident and shutdown failure parameters included in 100% leak release calculation

Component Failures

Component	Failure Mode	Distribution Type	Parameter A	Parameter B
Nozzle	Pop-off	Beta	0.5	610415.5
Nozzle	Failure to close	ExpectedValue	0.002	
Manual valve	Failure to close	ExpectedValue	0.001	
Solenoid valve	Failure to close	ExpectedValue	0.002	
Solenoid valve	Common-cause failure	ExpectedValue		

Accidents

Component	Failure Mode	Distribution Type
Overpressure during f...	Accident	Beta
Pressure relief valve	Failure to open	LogNormal
Driveoff	Accident	Beta
Breakaway coupling	Failure to close	Beta

Data/Probabilities

Probability data quantifying the events contained in the scenario models (ESDs and FTs)

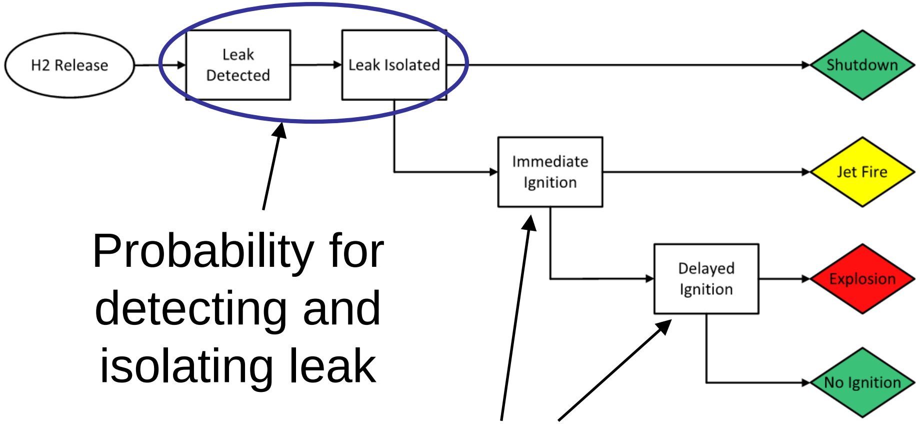
Component Leaks | Component Failures | Ignition Probabilities | Distributions

Compressors | Cylinders | Filters | Flanges | Hoses | Joints | Pipes | Valves | Instruments | Extra Component #1 | Extra Component #2

Leak Size	Mu	Sigma	Mean	Variance
0.01%	-1.7198	0.2143	1.83E-001	1.58E-003
0.10%	-3.9185	0.4841	2.23E-002	1.32E-004
1%	-5.1394	0.7898	8.01E-003	5.55E-005
10%	-8.8408	0.8381	2.06E-004	4.31E-008
100%	-11.3365	1.3689	3.04E-005	5.11E-009

Leak consequence determined with event diagram and probabilities

For a given hydrogen leak…



Probability for detecting and isolating leak

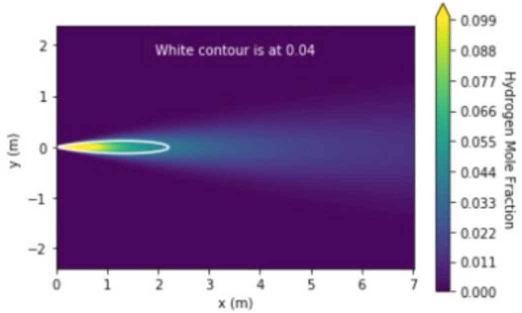
Probability of immediate or delayed ignition (varies with flow rate)

- Immediate ignition
  - Jet fire (thermal hazard)
  - Effect depends on occupant position
- Delayed ignition
  - Overpressure hazard
  - Not currently implemented fully
- For each hazard:
  - Probability of fatality for a given level of physical hazard
- Overall risk: total of all scenarios
  - Detailed results indicate what scenarios are driving overall risk

Underlying Python modules can be inspected, modified, and used independently

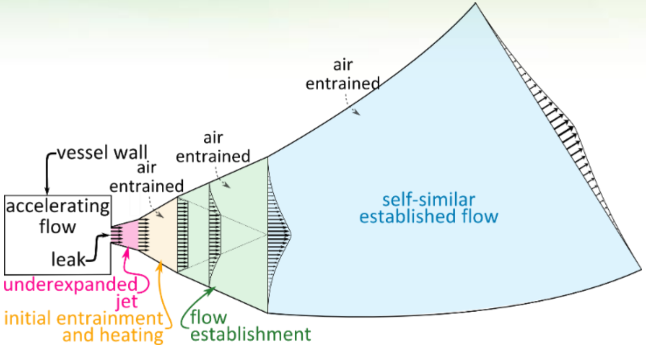
- Physics modules based on intuitive object oriented structure
- Implemented as a python package
- Additional details of simulations can be explored
- First access to upcoming module releases
- Incorporation of user-preferred physics models possible

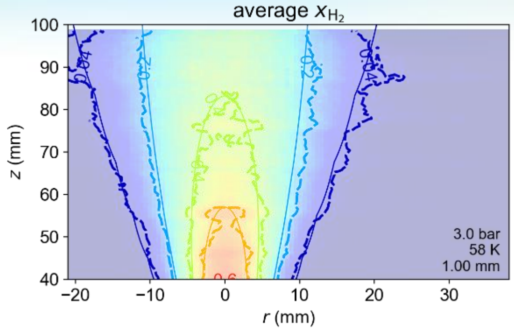
```
In [1]: from altRAM import phys

In [2]: H2 = phys.Gas(T = 40, P = 5e5);
        air = phys.Gas(T = 295, P = 101325, species =
        ['air']);
        orifice = phys.Orifice(d = 0.001);
        release = phys.Jet(H2, orifice, air);
        release.solve(Ymin = .001);
        release.plot_moleFrac_Contour();

        solving for the plume... done.
```



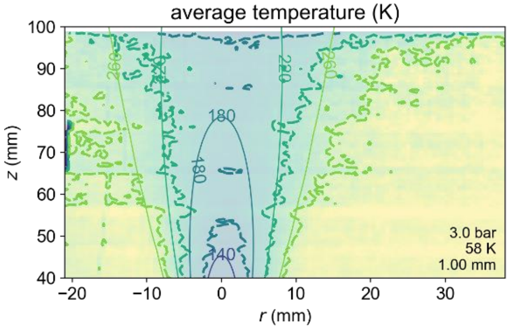
➢ Code organization, ease of use, and documentation critical for outside development/use

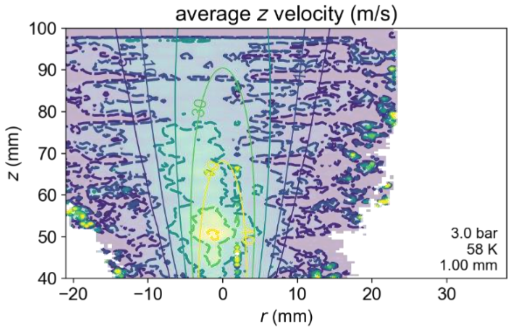
Upcoming ColdPLUME model has been validated with laboratory data





- Experimental results shown by shading and thick, dashed lines
- ColdPLUME model results are thin, solid lines





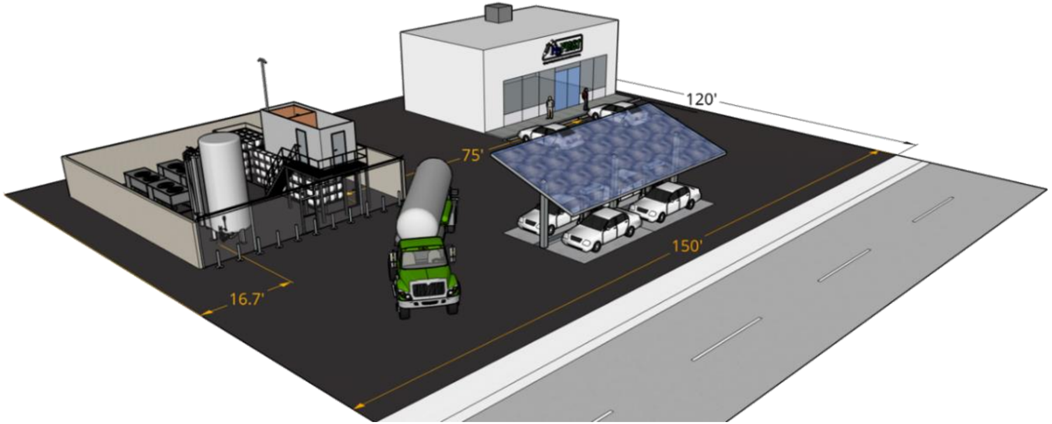
➢ Model accurately simulates mole fraction, temperature, and velocity - can be used as predictive tool

Upcoming additions to HyRAM

- Validated physics models for hydrogen behaviors
  - Liquid/cryogenic release behavior
  - Deflagration (unconfined) and detonation models
  - Flow/flame surface interactions
  - Pooling and vaporization
  - Barrier walls
  - Ignition
- Additional data/probabilities
  - Liquid hydrogen system component failures and leak frequencies
  - Effectiveness of detection
- Quantify risk reduction from hydrogen system mitigation features
- Extension to other fuels (e.g., CNG, LNG)

Summary

- HyRAM 2.0 is an open-source toolkit for QRA or physics simulations of hydrogen systems
- QRA and physics simulations can be used to inform siting decisions or separation distances
- Underlying source code can be used to explore the details of the calculations
- Sandia team is working to expand and enhance the toolkit
- External use, feedback, and development is welcomed and encouraged



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Thank you!

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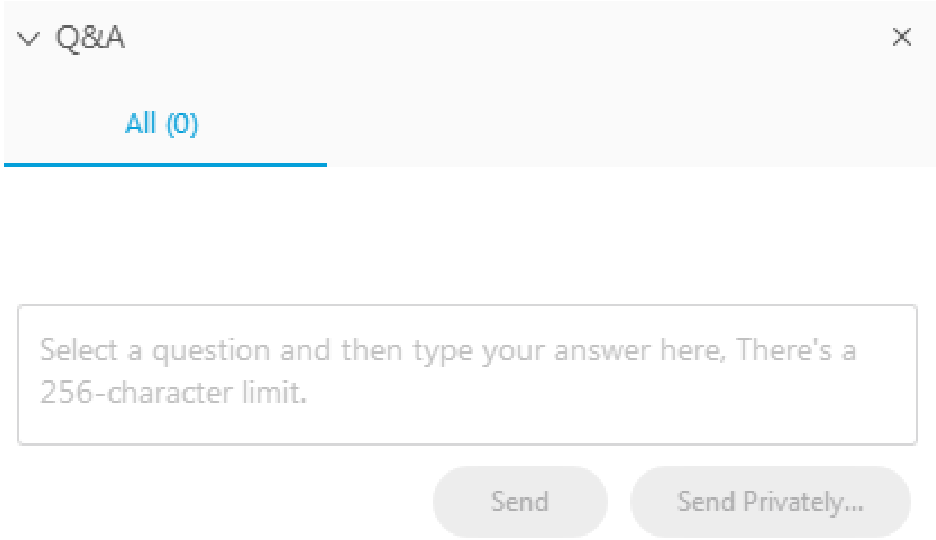
Research supported by DOE Fuel Cell Technologies Office (EERE/FCTO)

Question and Answer

- Please type your questions to the chat box. **<u>Send to: (HOST)</u>**



Thank you

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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?