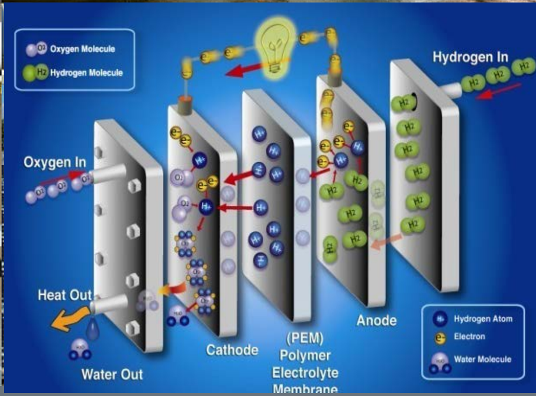
Overview of HyRAM Software for Science-Based Safety, Codes, and Standards

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



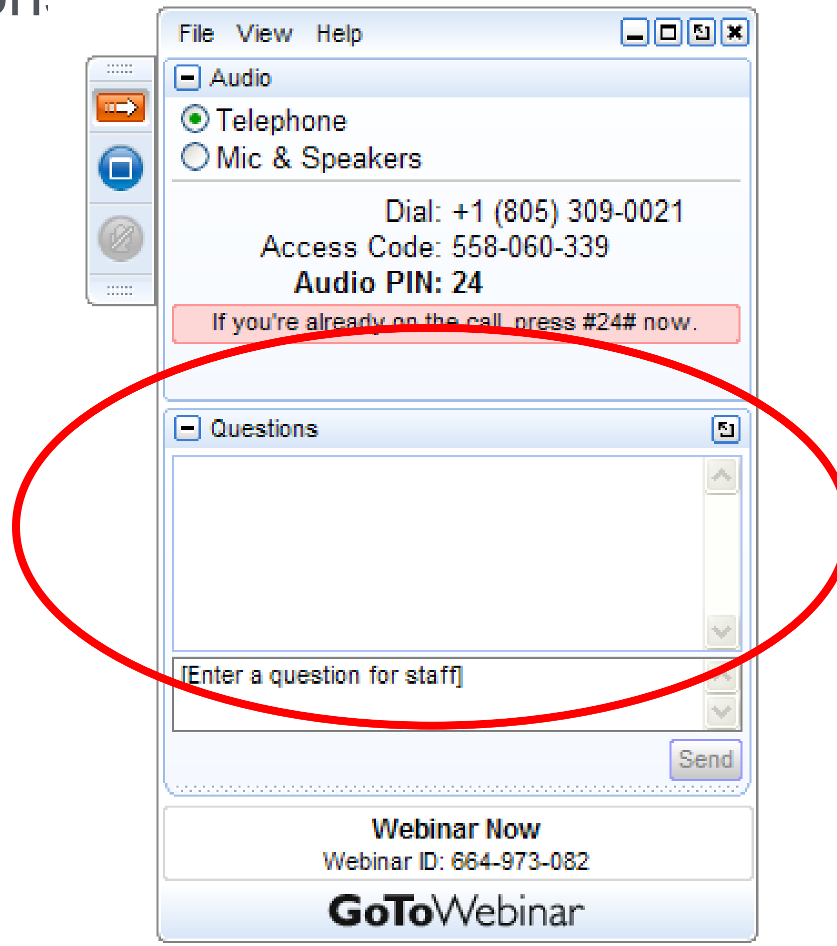
Presenter:
Katrina M. Groth – Sandia National Laboratories

DOE Host:
Will James – Program Manager: Hydrogen Safety, Codes, and Standards, Fuel Cell Technologies Office

U.S. Department of Energy
Fuel Cell Technologies Office
April 26, 2016

Question and Answer

- Please type your questions into the question box



HyRAM
HYDROGEN RISK ASSESSMENT MODELS

Overview of HyRAM Software for Science-Based Safety, Codes, and Standards

Katrina M. Groth
Sandia National Laboratories

Office of Energy Efficiency and Renewable Energy
Fuel Cell Technologies Office Webinar
April 26, 2016

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Webinar objectives

- Provide an overview of Sandia's program on Hydrogen Behavior and Risk Assessment
- Discuss HyRAM background, motivation, and application to reduce barriers to infrastructure deployment
- Demonstrate HyRAM V1.0 to stakeholders and current and future users

Coordinated activities to enable consistent, rigorous, and accepted safety, codes, and standards (SCS)

Risk R&D

Develop integrated methods and algorithms

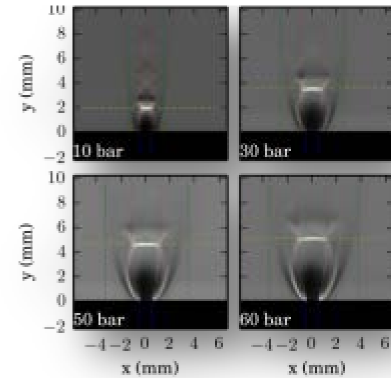
for enabling consistent, traceable and rigorous QRA

Application in SCS

Apply QRA & behavior models to real problems

in hydrogen infrastructure and emerging technology

Behavior R&D



Develop and validate scientific models

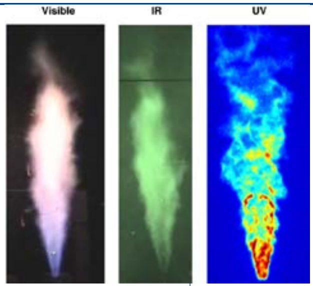
to accurately predict hazards and harm from liquid releases, flames, etc.

Enabling methods, data, tools

HyRAM
HYDROGEN RISK ASSESSMENT MODELS

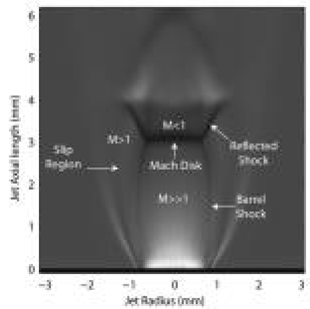
Hydrogen Behavior studies enable predictive capabilities

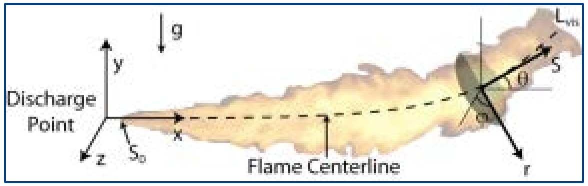
Radiative properties of H2 flames quantified



Barrier walls for risk reduction

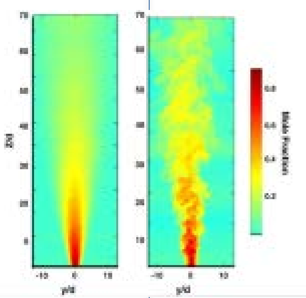
Ignition of under-expanded H2 jets





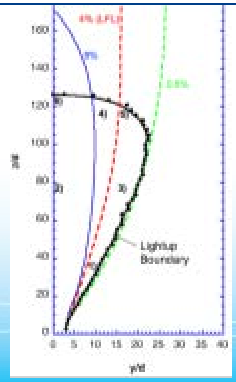
Buoyant jet flame model with multi-source radiation

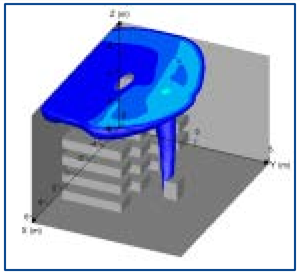
2005 | 2007 | 2009 | 2011 | 2013 | 2015 | 2017



Advanced laser diagnostics applied to turbulent H2 combustion

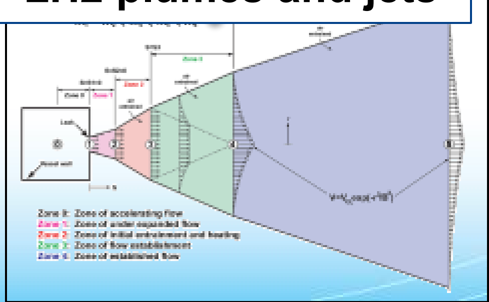
Ignition limits of turbulent H2 flows



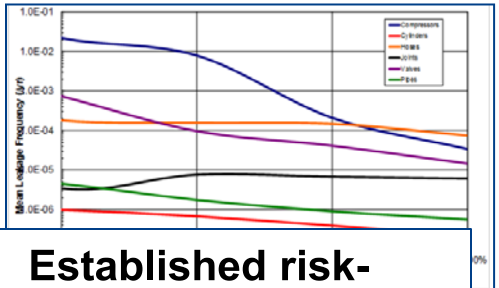


Experiment and simulation of indoor H2 releases

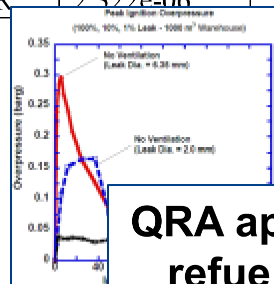
Laboratory-scale characterization of LH2 plumes and jets



Quantitative Risk Assessment enables evidence-based code development



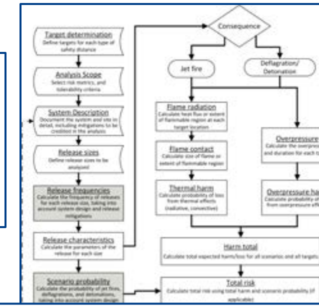
PLL	5.084e-04
FAR	0.1161
AIR	2.322e-06



Established risk-informed processes for separation distances

QRA applied to indoor refueling to inform code revision

Performance-based system layout demonstrated

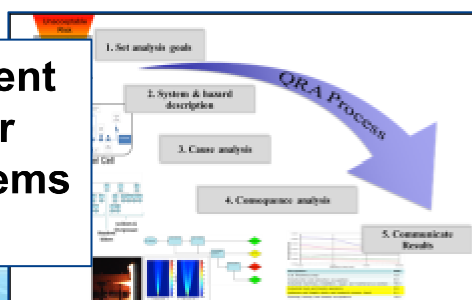


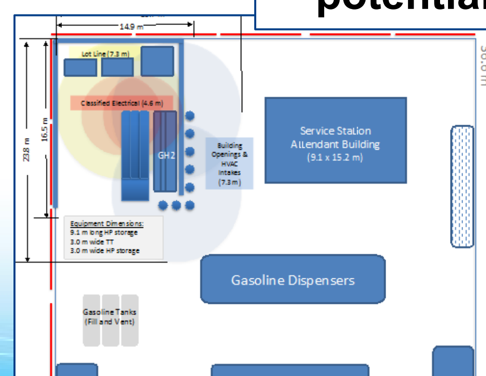
ISO TC197 WG24 incorporating QRA and behavior modeling

2005 2007 2009 2011 2013 2015 2017

Risk assessment proposed for hydrogen systems at ICHS

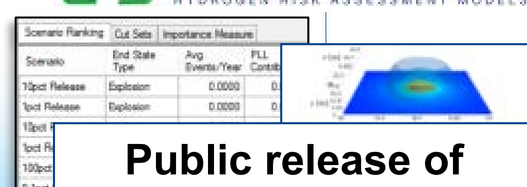
QRA-informed separation distances in NFPA 2





20% station penetration potential due to QRA

HYRAM HYDROGEN RISK ASSESSMENT MODELS



Public release of HyRAM R&D tool

What is Risk Assessment?

Risk = the potential for loss (more specifically, uncertainty about the potential for and severity of loss)

Risk Analysis		Risk Management

• A process used to identify and characterize risk in a system
  • What could go wrong?
  • How likely is it?
  • What are the consequences?
	+	• Provide inputs to decision makers on:
		  • Sources of risk
		  • Strategies to reduce risk
		  • Priorities

Note: One term, many methods! Can be qualitative or quantitative. Quantitative form referred to as QRA (Quantitative Risk Assessment)

HyRAM: Making hydrogen safety science accessible through integrated tools

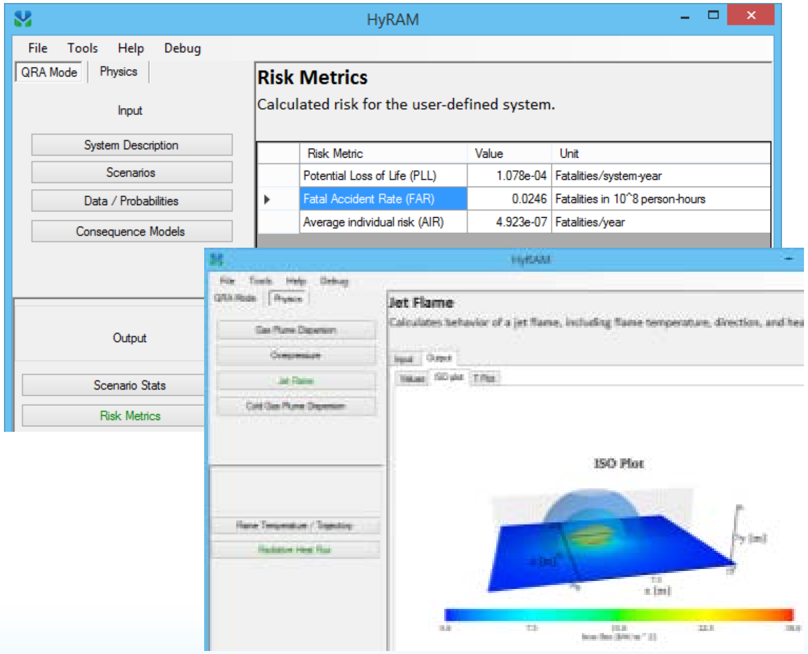
First-of-its-kind integration platform for state-of-the-art hydrogen safety models & data - **built to put the R&D into the hands of industry safety experts**

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



Free download at http://hyram.sandia.gov

HyRAM was developed to advance Sandia's impact on SCS

- **Direct impact on current H_2 SCS:**
  - **NFPA2 Ch. 7**: Established GH_2 separation distances (SAND2009-0874)
  - **NFPA2 Ch. 10**: Calculated risk from indoor fueling; identified ambiguity in requirements (SAND2012-10150)
  - **NFPA2 Ch. 5**: Enabling *Performance-based* compliance option (SAND2015-4500)
  - **ISO DTR-19880-1 Ch. 4**: Developing generalized approach for defining specific mitigations (e.g., safety distances) using regional criteria
- **Ongoing activities to develop and revise SCS**
  - **NFPA 2:** LH_2 separation distances , revision of GH_2 separation distances
  - **ISO DTR-19880-1:** develop DIS from the TR; develop of regional mitigation examples using SNL approach

HyRAM is also a tool that the community can use

- **Ongoing activities to develop and revise SCS**
  - **ISO DTR-19880-1:** Development of regional safety distances and mitigations using region-specific criteria

- **Additional possible areas of application:**
  - NFPA and ISO code revisions – enclosures;
  - Design insight –compare risk from different design options; understand which components drive risk/reliability (and which don't);
  - Assess quantitative mitigation credit (e.g., the risk importance of a gas detector)
  - Evacuation zone analysis
  - Insurance
  - As a teaching tool for hydrogen safety, QRA, and hydrogen behavior

HyRAM starting point: elements of high-quality QRA

- **Repeatability**
  - Defined objectives and scope;
  - Clear definitions of failure modes, consequences, criteria, models, and data
  - Document the system, assumptions,
- **Validity & Verifiability**
  - Data, models, system, and analysis must be sufficiently documented for a peer reviewer to evaluate assumptions, completeness, etc.
  - Use experimentally validated models (as available) and published models and data.
- **Comparability**
  - Necessitates flexible modeling tools, documentation of methodology
- **Completeness**
  - Ability to update models as knowledge improves
  - Ensure that analyzed system matches the system as built and operated

Major elements of HyRAM V1.0

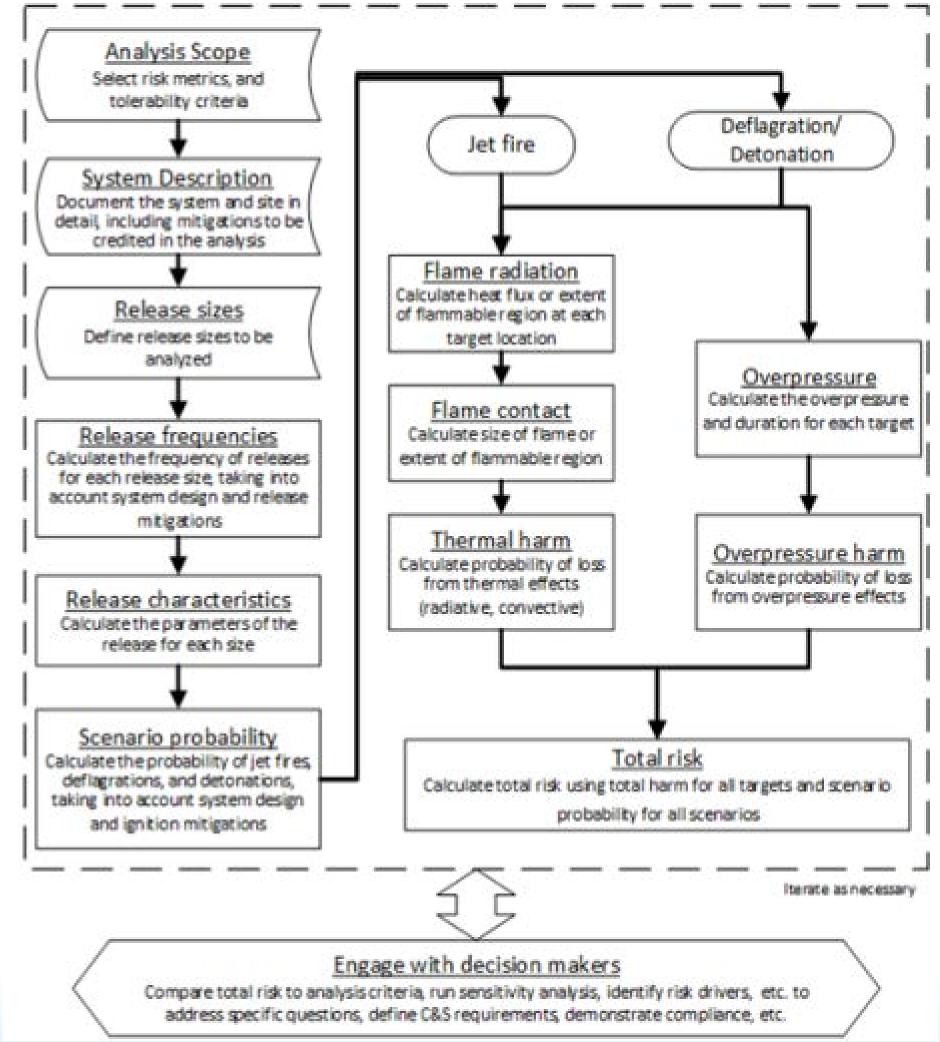
QRA Methodology
- Risk metrics calculations: FAR, PLL, AIR
- Scenario models & frequency
- Release frequency
- Harm models

Generic freq. & prob. data
- Ignition probabilities
- Component leak frequencies (9 types)

Physics (behavior) models
- Properties of Hydrogen
- Unignited releases: Orifice flow; Notional nozzles; Gas jet/plume; Accumulation in enclosures
- Ignited releases: Jet flames w/ and w/o buoyancy; overpressures in enclosures

Mathematics Middleware
- Unit Conversion System
- Math.NET Numerics

Documentation
- Published algorithms (SAND2015-10216)
- User guide (SAND2016-3385 R)



+ Software and documentation are available at http://hyram.sandia.gov

Making HyRAM an enduring safety assessment tool

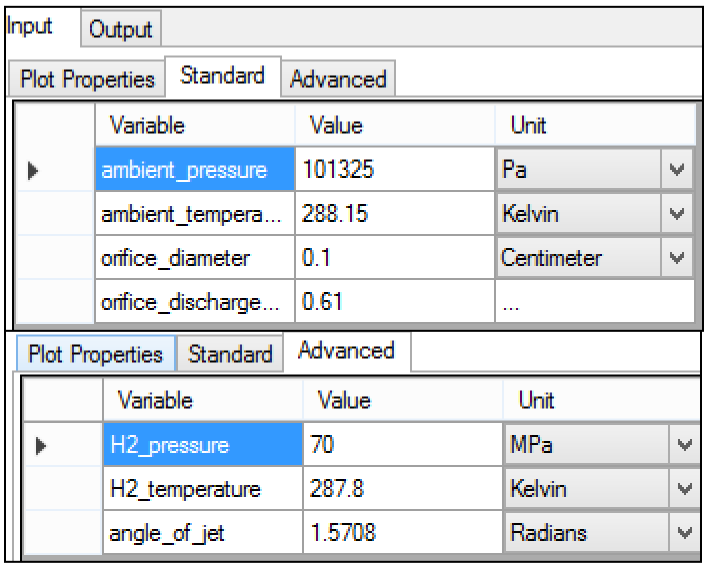
- *HyRAM methods have had direct impact on SCS via Sandia participation and FCTO investment. Transferring this technology to the hydrogen safety community amplifies that investment to further accelerate deployments.*

- Key considerations in taking HyRAM beyond single-user algorithms.
  - Graphical user interface, Windows platform, fast running
  - Data and models in HyRAM come from published sources
    - No proprietary information concerns; Users are able to override the defaults
  - Flexibility to meet a variety of user multiple goals
    - Enables implementation of QRA and hydrogen behavior (alone or together) to support a broad range of safety analyses
    - Default/generic assumptions to enable fast, high-level insights.
  - Open software architecture and growth mindset
    - Designed to enable updating data, models as information is generated
    - Framework to include multiple models for calculations; bringing in models beyond Sandia

Example of gas plume model (used for NFPA 2 safety distance to air intakes)

Input

- Release size & conditions



Input | Output

Plot Properties | Standard | Advanced

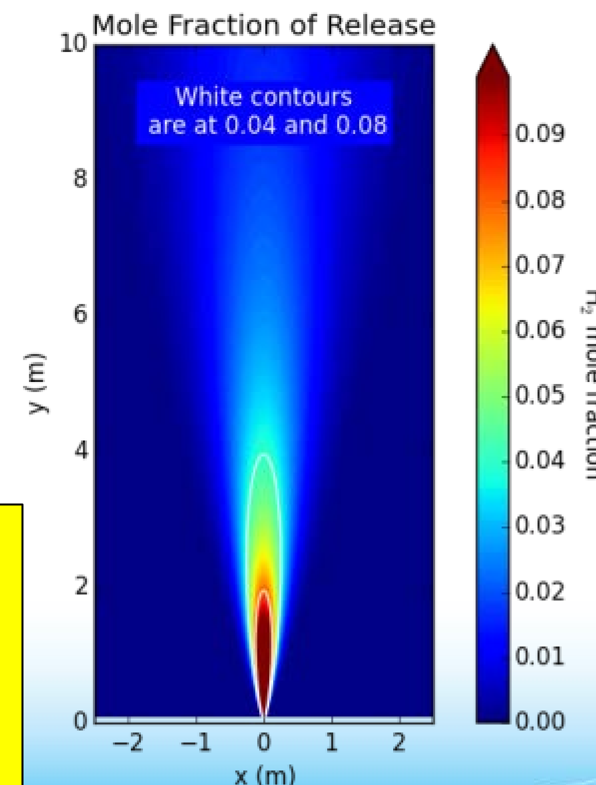
Variable	Value	Unit
ambient_pressure	101325	Pa
ambient_tempera...	288.15	Kelvin
orifice_diameter	0.1	Centimeter
orifice_discharge...	0.61	...

Plot Properties | Standard | Advanced

Variable	Value	Unit
H2_pressure	70	MPa
H2_temperature	287.8	Kelvin
angle_of_jet	1.5708	Radians

Output

- Gas concentration envelope for different safety (harm) criteria



- NFPA 2 (2011) GH2 safety distances used of 4% concentration as a harm criterion
- Illustration shows distance reduction that could be achieved by using 8% criterion rather than 4%. (Suggested change for NFPA 2 (2016) to remove conservatisms introduced by selection of 4% criteria)

Example of QRA model (used for NFPA 2 safety distance to lot line)

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 Temperature		
	Internal Pressure		
	External Temperature		
	External Pressure		

Components | System Parameters | Facility Parameters

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

nents | System Parameters | Facility Parameters

Occupants | Enclosure

Number of Targets	Description	Location Distribution Type	Location Distribution Parameter A	Location Distribution Parameter B	Location Parameter Unit	Exposed Hours Per Year
1	The person fueling the vehicle; assumed to be 1m from the dispenser	Deterministic	1		Meter	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

- NFPA 2 (2011) GH2 safety distances for "lot line" used AIR<=2e-5 for specific input conditions.
- In HyRAM, set those conditions and then iterate on "location" variable until AIR is below this criteria.

HyRAM Toolkit demo

Didn't attend the webinar? See backup slides for some example analyses.

Users and licensing

- **HyRAM V1.0 is a research prototype**
- HyRAM is designed for a Windows Platform. .NET software framework, written in C#, VB, Python.
- Free download of setup.exe with acceptance of license terms on website; after download users must request a free product registration key (valid for 1 year) via email.
- Intended users: experienced safety professionals, researchers, etc.
  - Early users include: PNNL, NREL, Paul Scherrer Institute, Linde, Shell, ITM Power, Zero Carbon Energy Solutions,

- Note: HyRAM does not say that a system is/is not "safe" because safety is not an equation.
  - *"We cannot replace difficult ethical and political deliberations with a mathematical one-dimensional formula"* (Aven, *Foundations of Risk Analysis, 2003*).

Looking forward

- **Long-term vision:** Partner with stakeholders to create a fully configurable, tested software product available for users to assess hydrogen risk and consequences; Able to support a wide range of activities within safety, codes, and standards and system design.

- **Ongoing Sandia research & development activities, including:**
  - R&D to create new data and models,
  - Developing a framework for user-contributed plug-ins
  - Extending QRA capabilities (e.g., Fault Trees, importance measures, uncertainty)

- **Need external H2 community** to lead or support formal software development , validation, testing, training, etc.
  - Currently exploring options for online wiki or forum for information exchange, community support , etc.

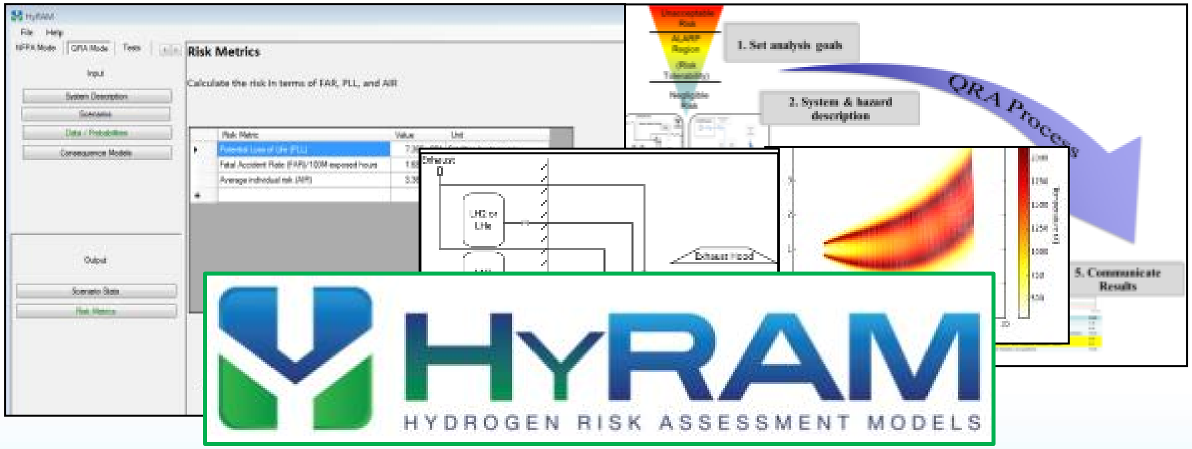
Summary

- **HyRAM is an integration platform** for state-of-the-art H2 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 in 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%."
- **Future applications:** Enabled by users

HyRAM is now available at http://hyram.sandia.gov

Thank you!

Research supported by the US Department of Energy's
Safety, Codes, and Standards (SCS) Program,
Fuel Cell Technologies Office (FCTO),
Office of Energy Efficiency and Renewable Energy (EERE)



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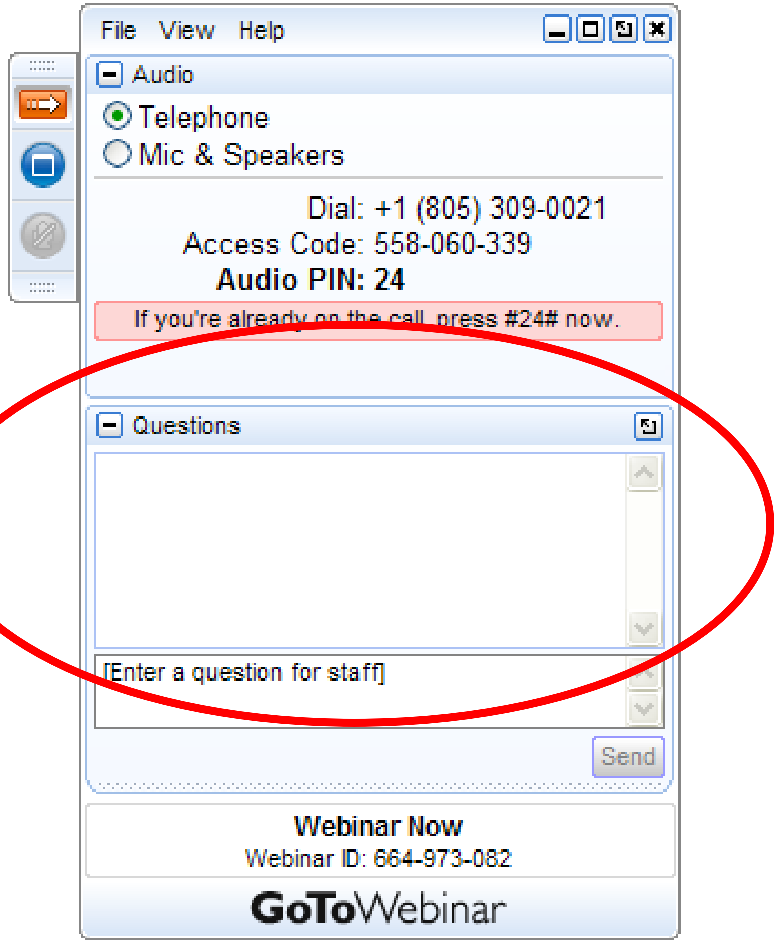
Question and Answer

- Please type your questions into the question box



Thank You

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  - Kgroth@sandia.gov

DOE Host:

- Will James – Program Manager, Hydrogen Safety, Codes, and Standards
  - Charles.James@EE.Doe.Gov

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Backup: HyRAM examples

Example: Full QRA (QRA mode)

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

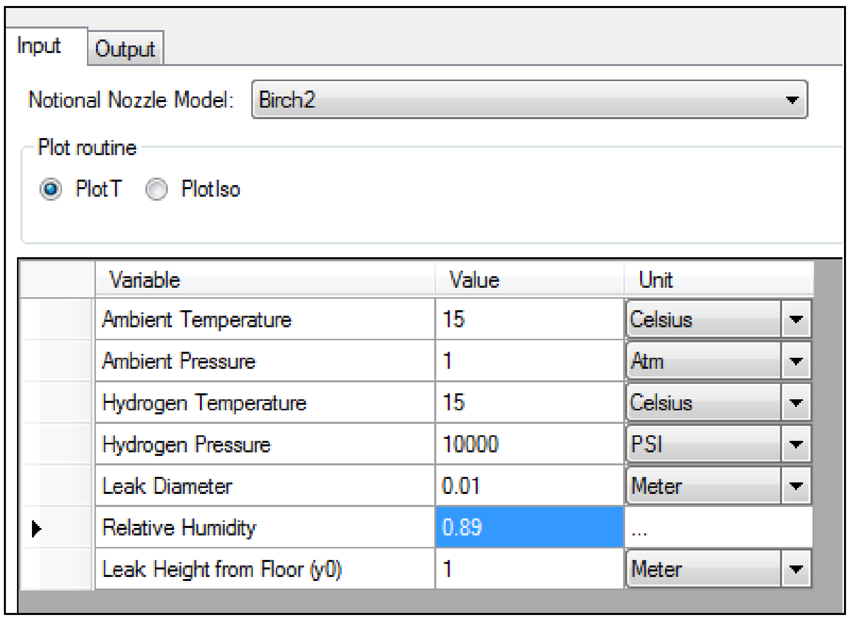
Scenario	End State Type	Avg. Events/Year	PLL Contribution
0.01pct Release	No Ignition	0.03448206	0.00%
0.1pct Release	No Ignition	0.00495318	0.00%
1pct Release	No Ignition	0.00148741	0.00%
10pct Release	No Ignition	0.00116683	0.00%
100pct Release	No Ignition	0.00071471	0.00%
0.01pct Release	Jet fire	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 %

Example: Jet Flame behavior (Physics mode)

Consequence-only modeling of ignited release

Input

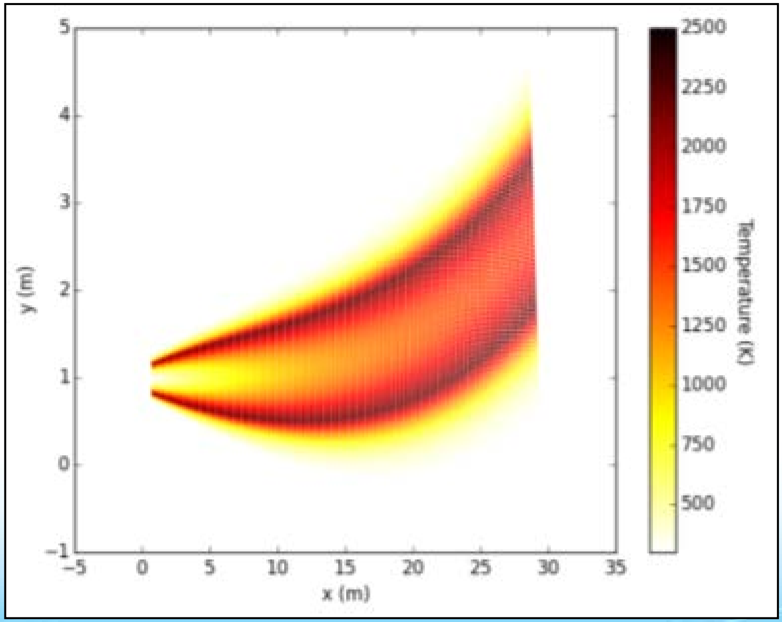
- Leak size and known conditions.



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.



Example: Gas plume dispersion (Physics mode)

Consequence modeling of unignited release

Input

- Release size & conditions

Input | Output

Plot Properties | Standard | Advanced

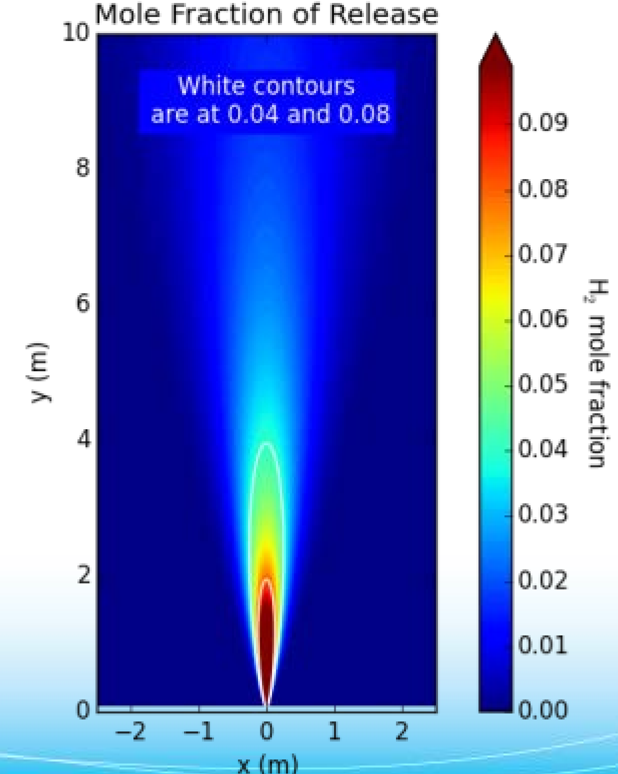
Variable	Value	Unit
ambient_pressure	101325	Pa
ambient_tempera...	288.15	Kelvin
orifice_diameter	0.1	Centimeter
orifice_discharge...	0.61	...

Plot Properties | Standard | Advanced

Variable	Value	Unit
H2_pressure	70	MPa
H2_temperature	287.8	Kelvin
angle_of_jet	1.5708	Radians

Output

- Gas concentration at different distances - direct analog to NFPA2 safety distance work

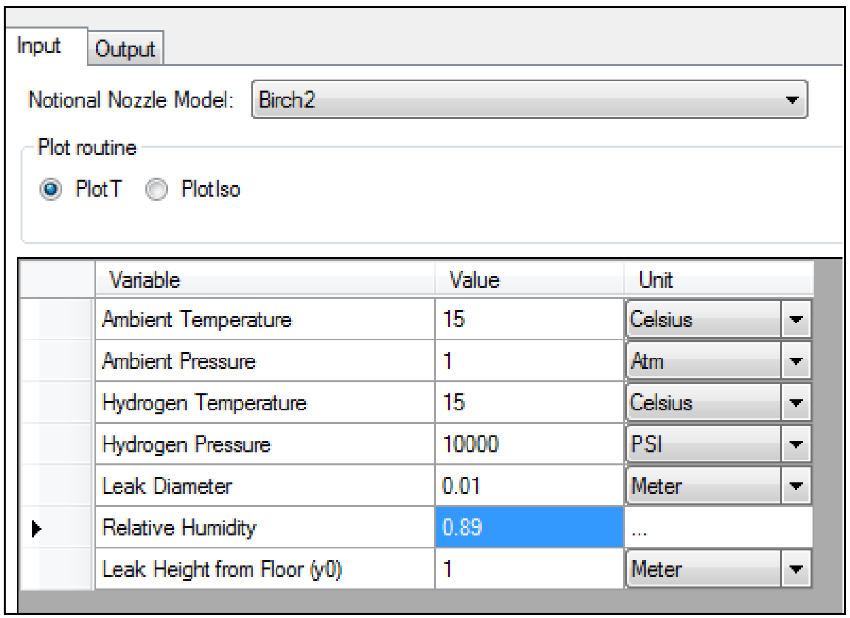


Example: Jet Flame behavior (Physics mode)

Consequence-only modeling of ignited release

Input

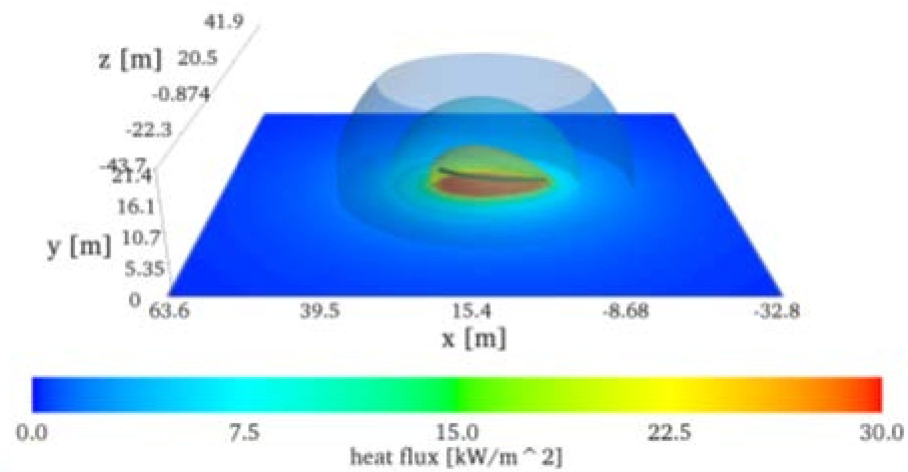
- Leak size and known conditions.



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

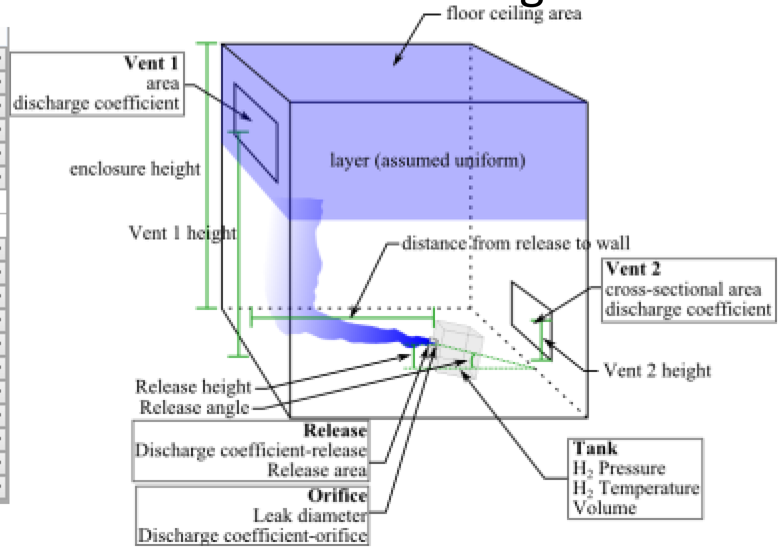
- Tabular data of heat flux at user-defined distances
- Shows heat flux boundaries for different harm criteria



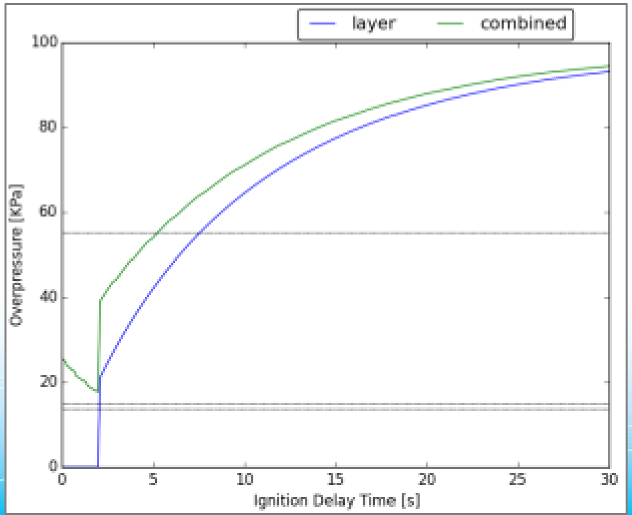
Example: Overpressure & layering in an enclosure

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



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

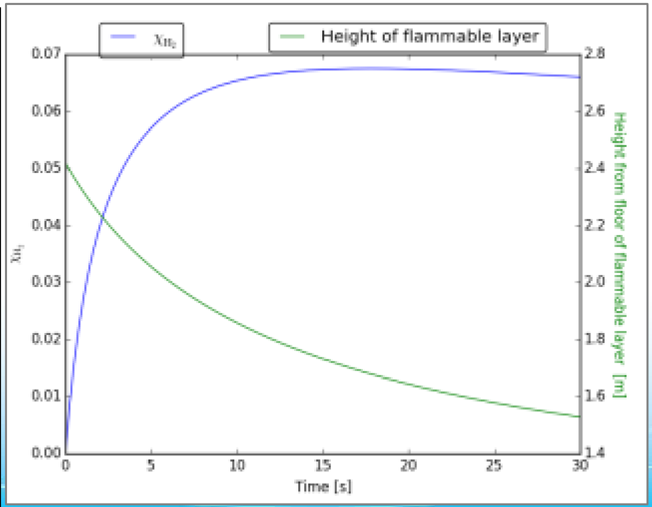


Maximum pressure (Pa): 94418.2835711473

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
16	8.294E+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
1.00806418	6.744E-002



Example: Engineering Toolkit

- Standalone functionality for simple calculations, e.g. density, tank volume/mass conversion, tank blowdown rate