Hydrogen Quantitative Risk Assessment

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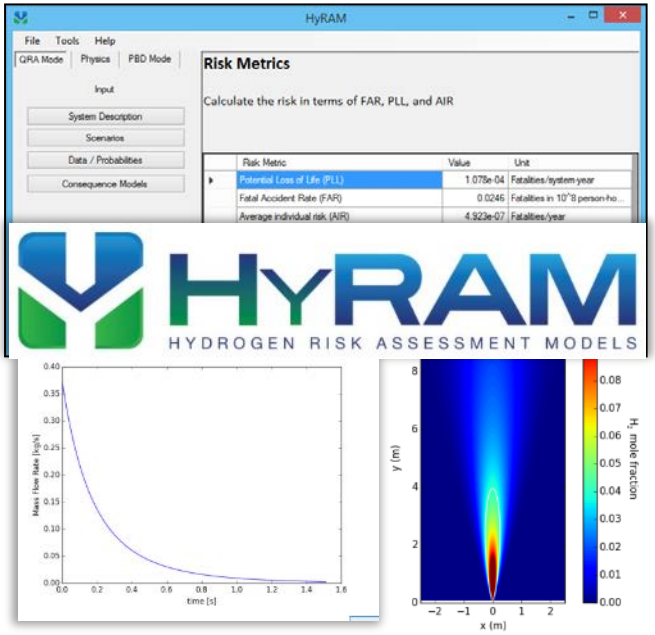

2018 DOE Hydrogen and Fuel Cells Annual Merit Review
June 13, 2018

Project # SCS011
SAND2018-0495 D

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Overview

Timeline

- Project start date: Oct. 2003
- Project end date: Sept. 2018*

  * Project continuation and direction determined by DOE annually.

Budget

- FY17 DOE Funding: $325k
- Planned FY18 DOE Funding: $325k

Barriers

A. Safety Data and Information: Limited Access and Availability
F. Enabling National and International Markets Requires Consistent RCS
K. No Consistent Codification Plan and Process for Synchronization of R&D and Code Development
L. Usage and Access Restrictions – Parking Structures, Tunnels and Other Usage Areas

Partners

Industry & research collaborators:
Linde, First Element, PNNL, NREL, Air Liquide, Quong & Associates, 40+ organizations using HyRAM

SDO/CDO participation:
NFPA 2, H2USA, CaFCP, FPRF

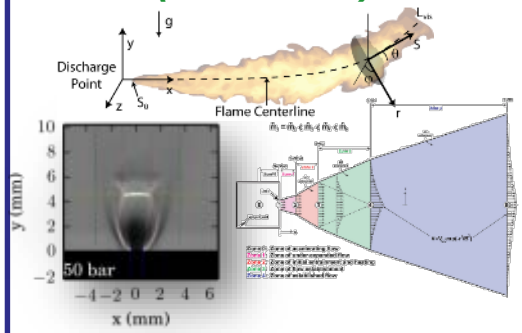
Relevance

Objective: Develop a rigorous **scientific & engineering basis** for assessing safety risk of H_2 systems and **facilitate use of that information** for revising RCS for emerging hydrogen technologies.

Barrier from 2015 SCS MYRDD	SNL Goal
A. Safety Data and Information: Limited Access and Availability	Build validated H2 behavior physics models that enable industry-led C&S revision and Quantitative Risk Assessment (QRA).
F. Enabling National and International Markets Requires Consistent RCS	Develop H_2-specific QRA tools & methods which support SCS decisions.
K. No Consistent Codification Plan and Process for Synchronization of R&D and Code Development	Apply H2-specific QRA tools & methods to support code improvement and to enable risk-equivalent code compliance option.
L. Usage and Access Restrictions – Parking Structures, Tunnels and Other Usage Areas	Develop scenario specific analysis of hydrogen behavior and consequences and evaluate mitigation features.

Project Approach: *Coordinated activities* to enable consistent, rigorous, and accepted safety analysis

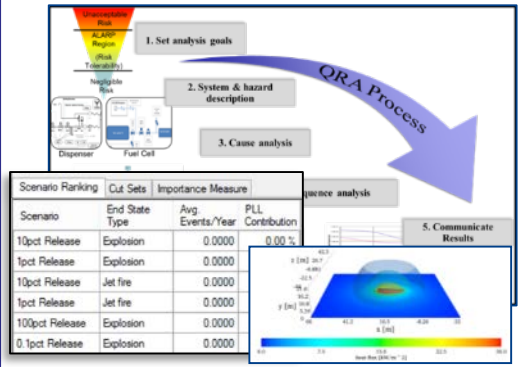
Behavior R&D (SCS 010)



Develop and validate scientific models

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

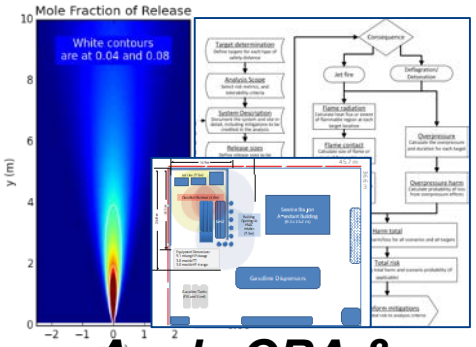
Risk R&D (SCS 011)



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

Approach / FY17-18 Milestones

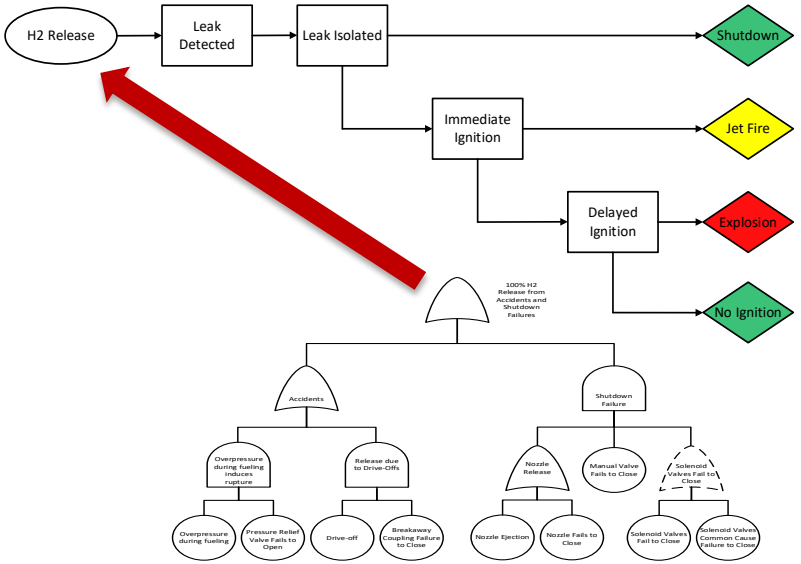
Impact Areas	Completion date or status
Expanding HyRAM capabilities and essential maintenance	
• Develop & integrate QRA flexibility into HyRAM • Licensing, distribution, bug reporting, bug fixes, testing • Publish HyRAM V1.1 User Guide • Incorporate ColdPlume model into HyRAM to support LH2 analysis	On track for Sept 2017 Ongoing / as needed Jan. 2018 2019
Update Gaseous Separation Distances Based on Revised Risk Criteria	
• Address public comments, recalculate for second draft of NFPA 2 • Participate in NFPA 2/55 code committee meetings	Mar. 2017 On track for Jul 2018
Evaluate feasibility of using QRA, materials info for H2 storage technologies	
• Literature review and gap study • Report on state-of-the-art and R&D needs	Aug. 2017 Sept. 2017
Evaluation of Existing Tunnel for FCEV Safety	
• Developed Heat Transfer and CFD models of Tunnel Fire • Brief AHJs in Boston and NY/NJ on risk analysis and modeling results • Published tunnel report documenting project results	Sept. 2017 Sept./Oct. 2017 Oct. 2017

Progress: Expanding HyRAM QRA flexibility beyond hydrogen refueling stations

- Goal: Develop additional QRA capability to enable HyRAM to be applied to a larger variety of H2 applications
- Approach:
  - Incorporate HyRAM methodology that enables users to alter the risk analysis for different applications
  - Users will be able to edit the parameters of the existing fault tree (FT) or substitute their user-defined FT results from external FT software

Risk Metric	Value	Unit
Potential Loss of Life (PLL)	2.146e-05	Fatalities/system-year
Fatal Accident Rate (FAR)	0.0245	Fatalities in 10^8 person-ho...
Average individual risk (AIR)	6.556e-07	Fatalities/year

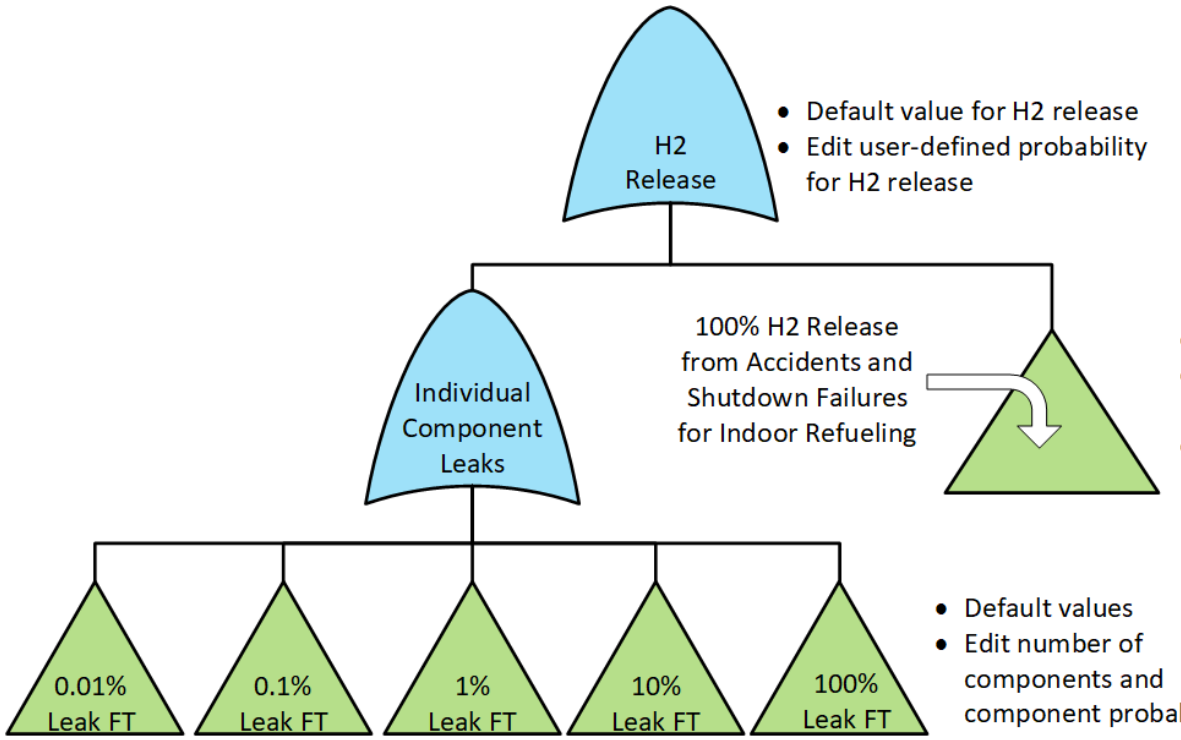
$$Risk \propto \sum_{i,j,k} P(\text{Release}_i) P(\text{Ignition}_j | \text{Release}_i) P(\text{Hazard}_k | \text{Ignition}_j \cap \text{Release}_i) P(\text{Harm} | \text{Hazard}_k)$$



Expanded QRA ability will allow for hydrogen safety analysis for new H2 technologies.

Progress: Expanding HyRAM QRA flexibility beyond hydrogen refueling stations

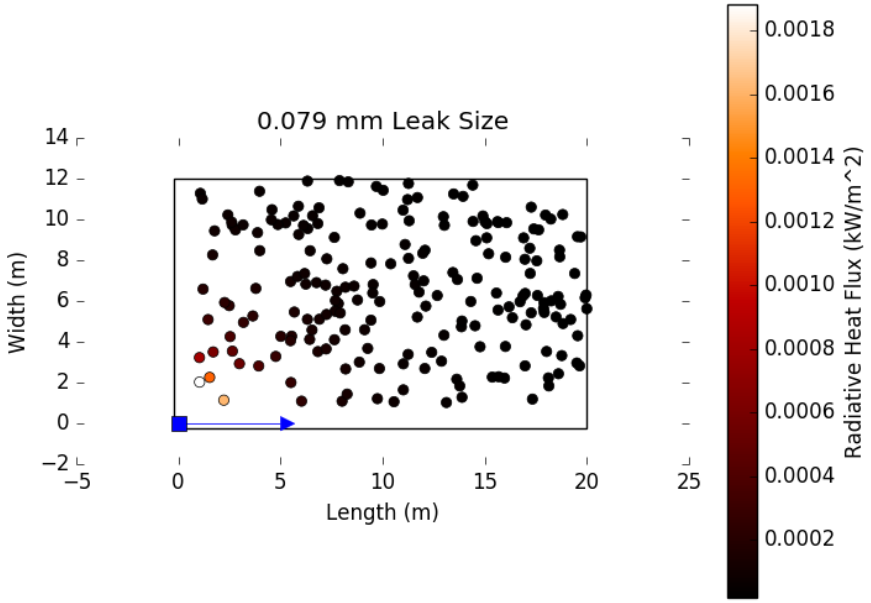
- Progress:
  - Determined methodology and feasibility to customize QRA
  - Developed scenarios of concern to ensure that this update will meet the needs of all new and emerging H2 technologies
  - Updates to software currently in development



User-defined component failure rates or entire FT results could be utilized to provide ultimate flexibility

Accomplishment: HyRAM quality review, testing, maintenance

- On-going conversion of backend from C# to Python
  - Ease expansion of software for other applications (i.e. liquid H2 models)
  - Review QRA calculations for quality assurance
- Critical bug fixes
  - Improved and clarified user interface
  - Corrected calculation issue for large number of occupants



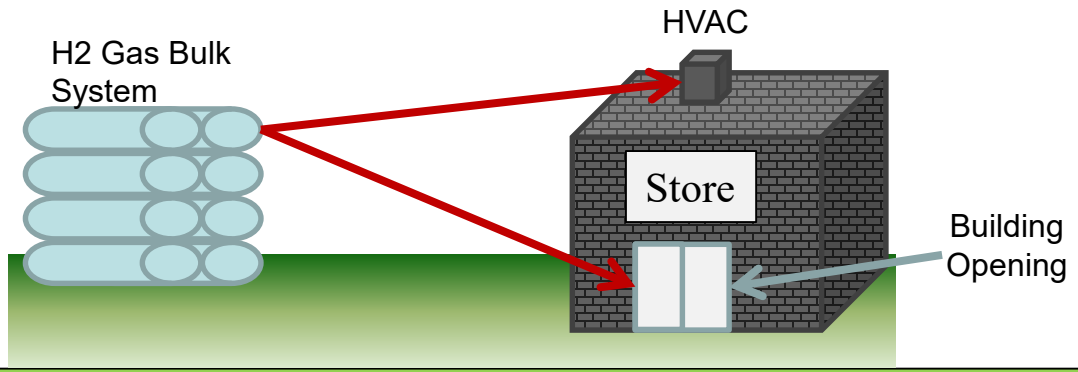
- Quality assurance efforts are essential for user confidence, usability
- Important step in transitioning SNL technologies, R&D to H2 industry

Progress: Science-based gaseous separation distances

- Goal: Update NFPA 55/2 gaseous separation distances using scientific justification for risk criteria
- Progress:
  - Gaseous revision table was accepted by TC 55/2 for the first draft meeting
  - Edits to the first draft have been made to the appendix and the tables to ensure accuracy
  - HyRAM used to calculate consequences from H2 releases

Exposures	Code Version	Separation Distance			
		>0.10 to 1.72 MPa	>1.72 to 20.68 MPa	>20.68 to 51.71 MPa	>51.71 to 103.43 MPa
Group 1 Exposures	2016	12 m	14 m	9 m	10 m
	2019	**5 m**	**6 m**	**4 m**	**5 m**
Group 2 Exposures	2016	6 m	7 m	4 m	5 m
	2019	**5 m**	**6 m**	**3 m**	**4 m**
Group 3 Exposures	2016	5 m	6 m	4 m	4 m
	2019	**4 m**	**5 m**	**3 m**	**4 m**

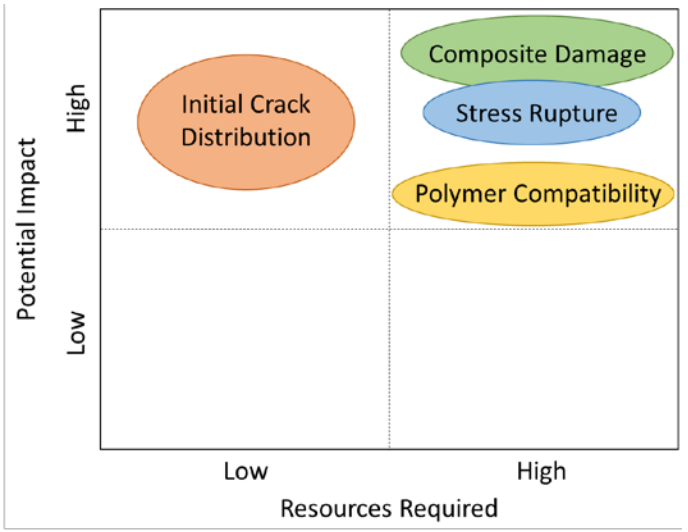
2016: 10 m for 70 MPa storage
2020: 5 m for 70 MPa storage



Risk-informed code requirements based on risk threshold revisions enable more sites to readily accept hydrogen infrastructure

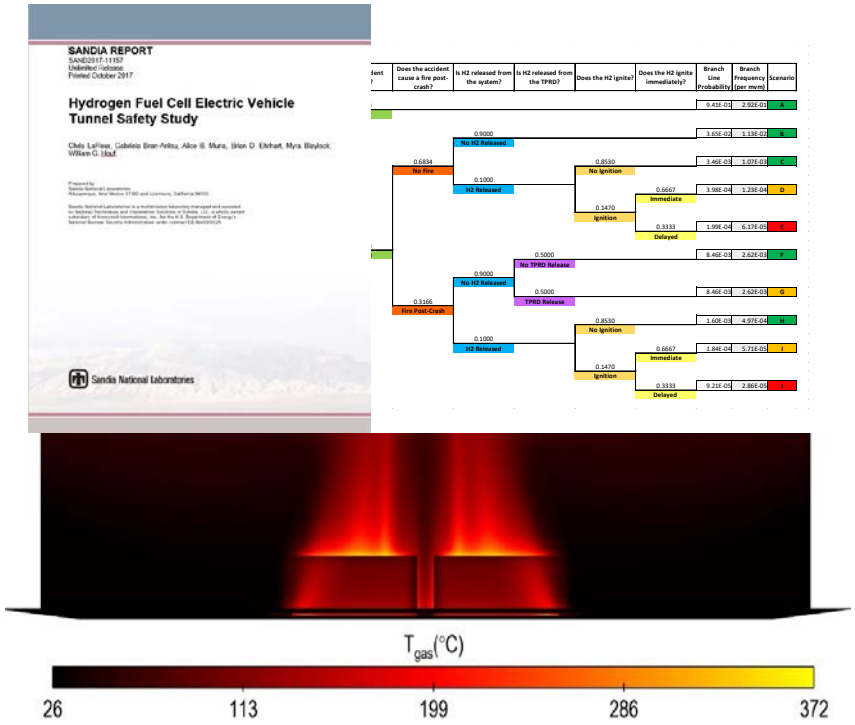
Accomplishment: Identification of gaps in hydrogen material risk challenges

- Goal: Leverage foundational R&D capabilities in QRA and materials to characterize and calculate risk associated with a key H_2 infrastructure gap (storage)
- Progress:
  - Reviewed literature on known R&D gaps
  - Identified and prioritized four areas of risk application to hydrogen materials based on specificity, level of anticipated resources required, and potential impact to the field.
  - Determined that quantification of the behavior of stress rupture for composite cylinders was the area of most interest given SNL capabilities and impact



- Potential impact on multiple FCTO program elements: Safety Codes and Standards, Delivery, and Storage
- Leveraging SNL H2 program core capabilities (risk, materials), and other SNL programs (scientific computing) to address critical barriers for industry

Accomplishment: Hydrogen fuel cell electric vehicle tunnel safety study published Oct. 2017



- Report released Oct. 2017 download at: http://energy.sandia.gov/transportation-energy/hydrogen/quantitative-risk-assessment/
- Documented risk analysis framework which identified scenarios of concern
- Coupled CFD and heat transfer models to evaluate hydrogen fire impact on steel structure and explosive spalling of concrete
- Details given in SCS-025 AMR presentation

Risk analysis and modeling results will be communicated to AHJs to assist in their decision-making.

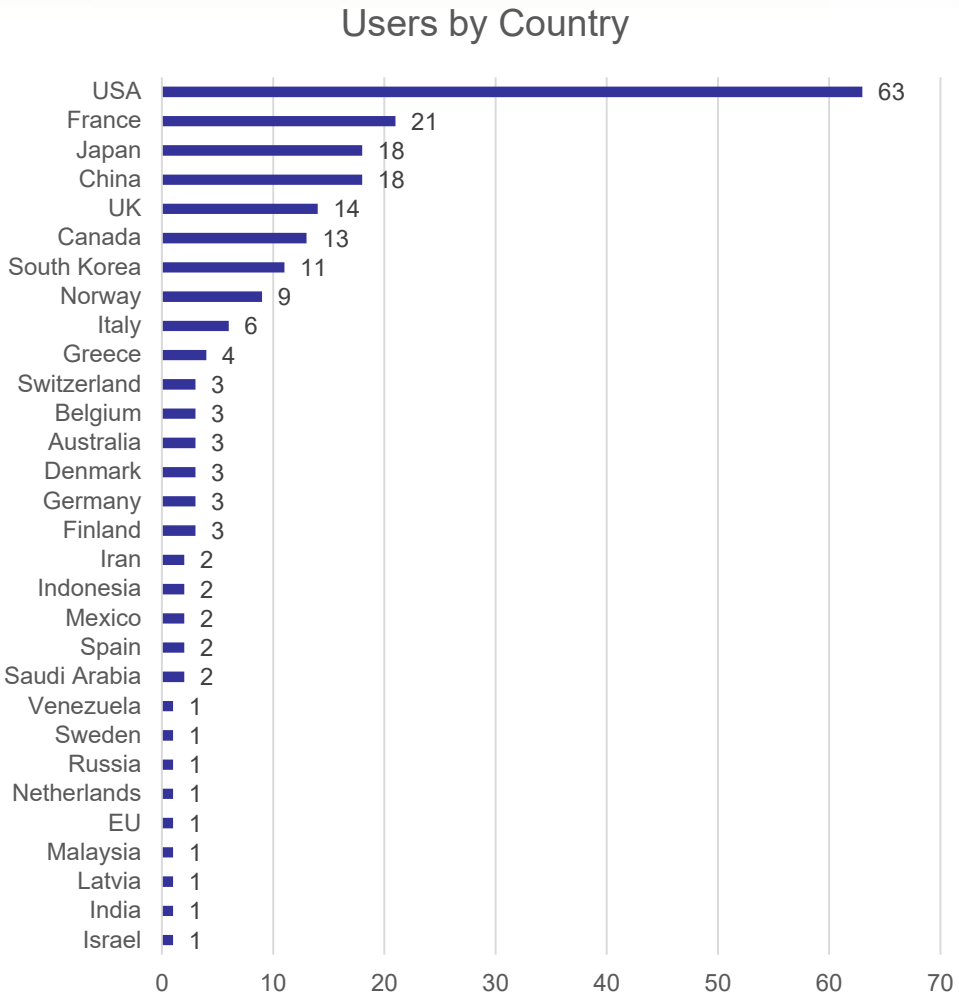
Responses to previous year reviewer's comments

- *AMR2017 comment: Liquid hydrogen should be added as quickly as possible.*
  - We will begin incorporating models for cryogenic hydrogen releases into HyRAM once the validation experiments in SCS010 have been completed. We anticipate this will occur in FY19.
- *AMR2017 comment: Further broadening the focus on other public aspects of the technology would offer an important support to safety design in other areas. For example, a module dedicated to storage technologies would be important to answering many questions of local regulators.*
  - There are many areas where additional modules and data could enhance the RCS and adding flexibility to the QRA portion of HyRAM will allow for analyses to be conducted for more applications.
- *AMR2017 comment: The only suggestion is even more outreach, such as articles published in a variety of trade journals, to increase awareness and use of the models. This may facilitate obtaining further data, support, and partners.*
  - We are beginning to explore these possibilities with the new CRADA collaborations with industry.

Collaborations: Partners, RCS participation & international engagement

Relationship	Partner	Role
CRADA (Signed)	**Linde Group**, Industrial gas supplier	In-kind support, data exchange for QRA tool, PBD activities, LH2 laboratory
CRADA (Signed)	**First Element Fuel**, Station Developer	In-kind support, data exchange for QRA tool, PBD activities
CRADA (Signed)	**Frontier Energy (Manager of the California Fuel Cell Partnership)**	Develop industry stakeholders in support of LH2 Behavior Characterization
CRADA (Signed)	**Fire Protection Research Foundation (NFPA)**	Lead stakeholder oversight panel and enable link to NFPA code process
CRADA (Not Yet Signed)	**Air Liquide**, Industrial gas supplier	Research on LH2 releases and QRA
CRADA (Not Yet Signed)	**Quong & Associates**, Industry consultants	Research on GH2 releases in maintenance facilities
Code Committee Members	**NFPA 2, 55**	Separation distances task group, enclosures task group, and permitting task group.
Collaborator	**Pacific Northwest National Laboratory**	Hydrogen tools portal, Hydrogen Safety Panel, hydrogen mitigations forum
Collaborator	**National Renewable Energy Laboratory**	Technical exchanges on QRA, safety codes and standards committees and task groups

Collaborations & Tech Transfer: HyRAM active users span stakeholder groups, applications, countries



- 115 users who have obtained free license keys in FY18
  - 57 renewal keys, 58 new users
- Users include:
  - **US labs & regulators**: SNL, NREL, PNNL, NASA; Hawaii Natural Energy Institute
  - **Gas suppliers**: Air Liquide, Linde, Shell, Indian Oil
  - **Universities**: UQTR (CA), UNAM (Mx), YNU (JP), WSU, Sheffield (UK) Ulster (UK), DTU (DK), CAU (KOR), HU (KOR), UHM, HSN (NO)
  - **Int'l labs & regulators**: PSI (CH), NMRI (JP), KGS (KOR); RIVM (NL), Bureau Veritas Marine (FR); IPMO, VTT (FIN)
  - **Manufacturers**: H2Logic; Plug Power, Inc.; PowerTech Labs; Kawasaki, Michelin
  - **Consulting**: Arcola Energy, AVT, CNL, Zero Carbon Energy Solutions, Witte Engineered Gases; FonCSI; Lilleaker Consulting AS; HNTB Corporation; Jacobs Technology; IntelliSIMS, Fp2Fire, Neodyme; The IET

Remaining challenges & barriers

- Science-based Code Improvements
  - Incorporate **validated physics models for hydrogen behaviors**, including: liquid/cryogenic release behavior; deflagration (unconfined) and detonation models, flow/flame surface interactions, barrier walls, ignition, etc.
  - **Generate data/probabilities** for hydrogen system component failures, leak frequencies, detection effectiveness, etc. based on operating experience or other information
  - Develop **uncertainty & sensitivity analysis** capabilities for HyRAM
- Hydrogen Tunnel Safety
  - Acceptance by local AHJ may be on a case-by-case basis since each tunnel is unique

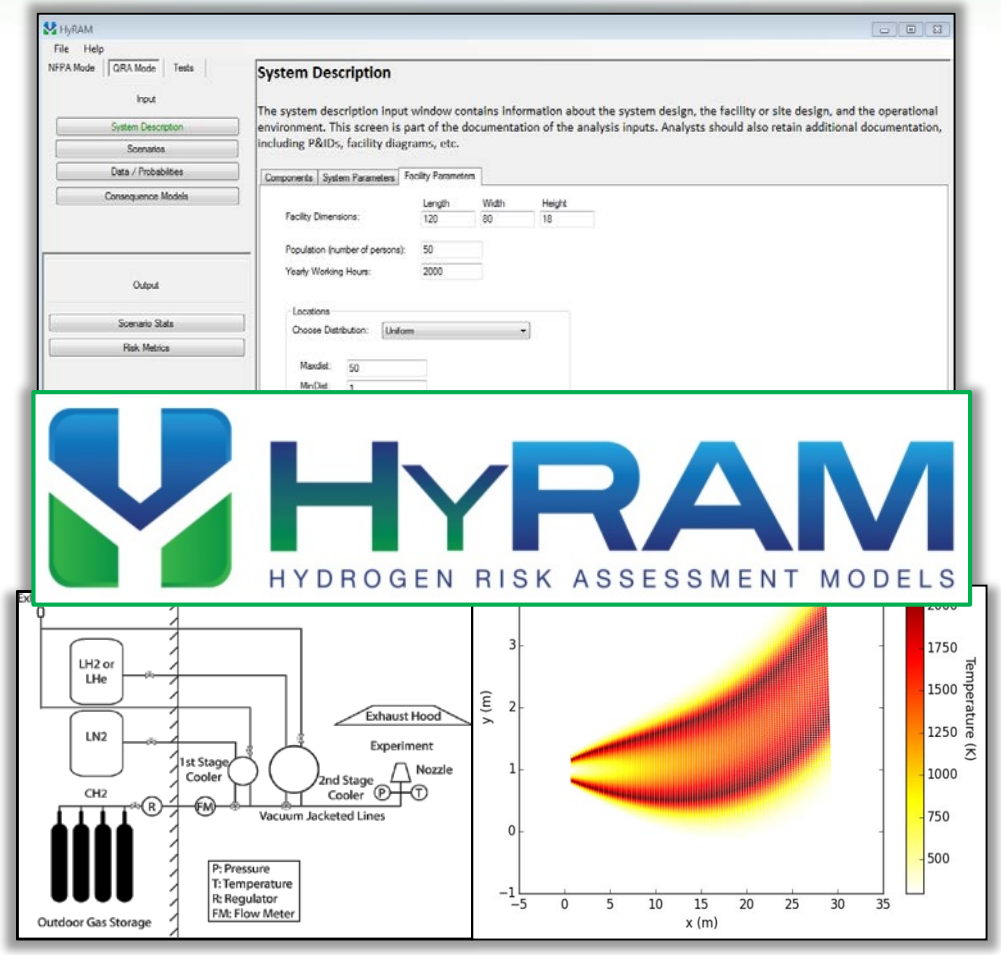
Proposed future work

- Rest of FY18:
  - Incorporate QRA flexibility into HyRAM and distribute as HyRAM 2.0
  - Support development of a PBD/alternative means for a First Element station
  - Publish the report on materials risk challenges
- FY19:
  - Refine characterization of LH2 releases with validated cold plume release and identify full scale modeling needs to provide sound scientific basis for revised bulk LH2 separation distances in NFPA 2/55.
  - Develop GUIs & source code for cold-plume model based on experimental results

- Any proposed future work is subject to change based on funding levels

Technology transfer activities

- Technology transfer strategies are tied to the accessibility of HyRAM QRA tool kit to other users (AHJs, station designers, etc.) to analyze station risks or consequences-only
- Free HyRAM download at http://hyram.sandia.gov



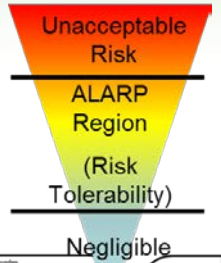
Current release is version 1.1.1.1249

Summary

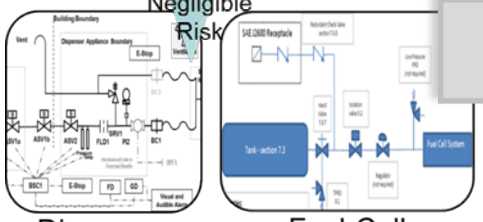
- **Three-pronged R&D approach:** two R&D activities (SCS011, 010) feeding C&S development (SCS025)
  - Provide science & engineering basis for assessing safety (risk) of H2 systems and facilitate use of that information in RCS and permitting
  - Coordinated activities ensures: Accelerated transfer of R&D results into codes and standards; R&D focused on high-impact stakeholder problems
- **Reducing barriers** related to limited availability and access to safety data for RCS revision
- **Technical Accomplishments:** Quality assurance and GUI improvements to HyRAM; Identification of gaps in materials risk R&D; Updated gaseous separation distances in NFPA 55/2; H_2 FCEV tunnel safety study
- **Future Work**: Improvements to HyRAM QRA calculations for added flexibility; performance based design for real world H_2 refueling station; develop and test cold plume model for LH2 releases

Technical Back-Up Slides

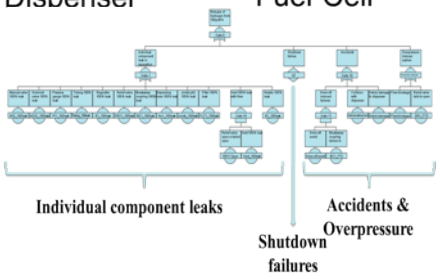
The art and science of QRA



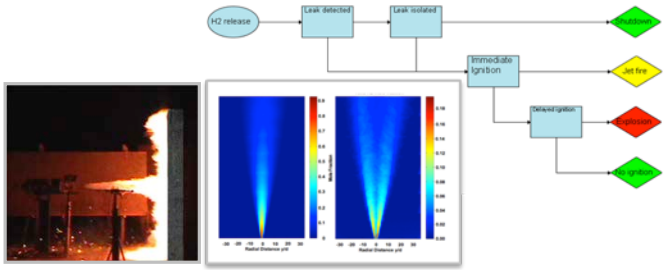
1. Set analysis goals



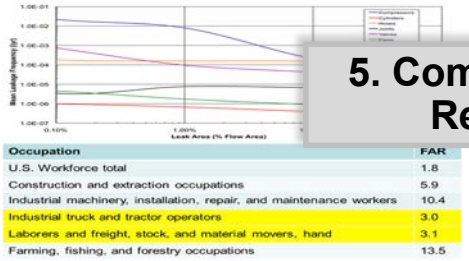
2. System & hazard description



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 analyst can establish own analysis goals, defines own system

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

HyRAM: Making hydrogen safety science accessible through integrated tools

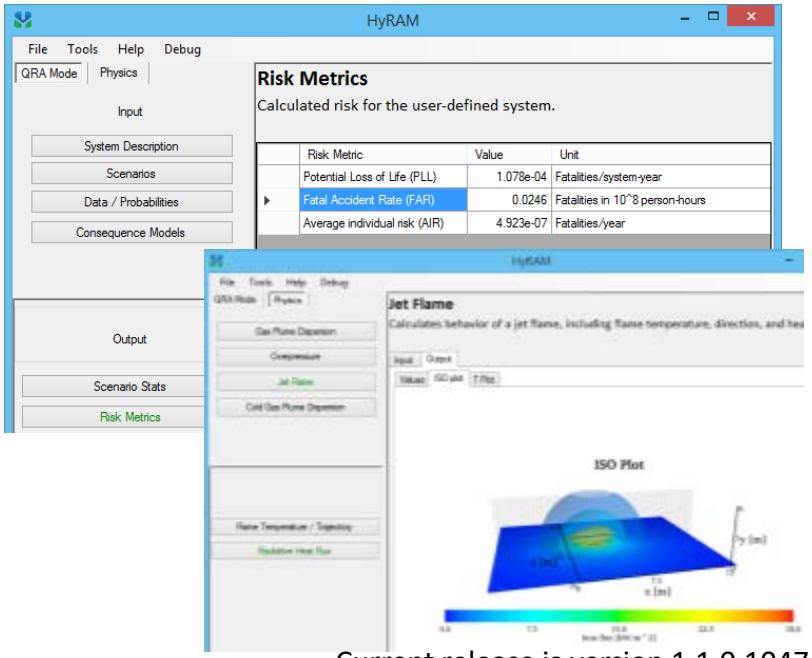
First-of-its-kind integration platform for state-of-the-art hydrogen safety models & data - **built to put the R&D into the hands of industry safety experts**

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 1.1.0.1047

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

Major elements of HyRAM software

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 models

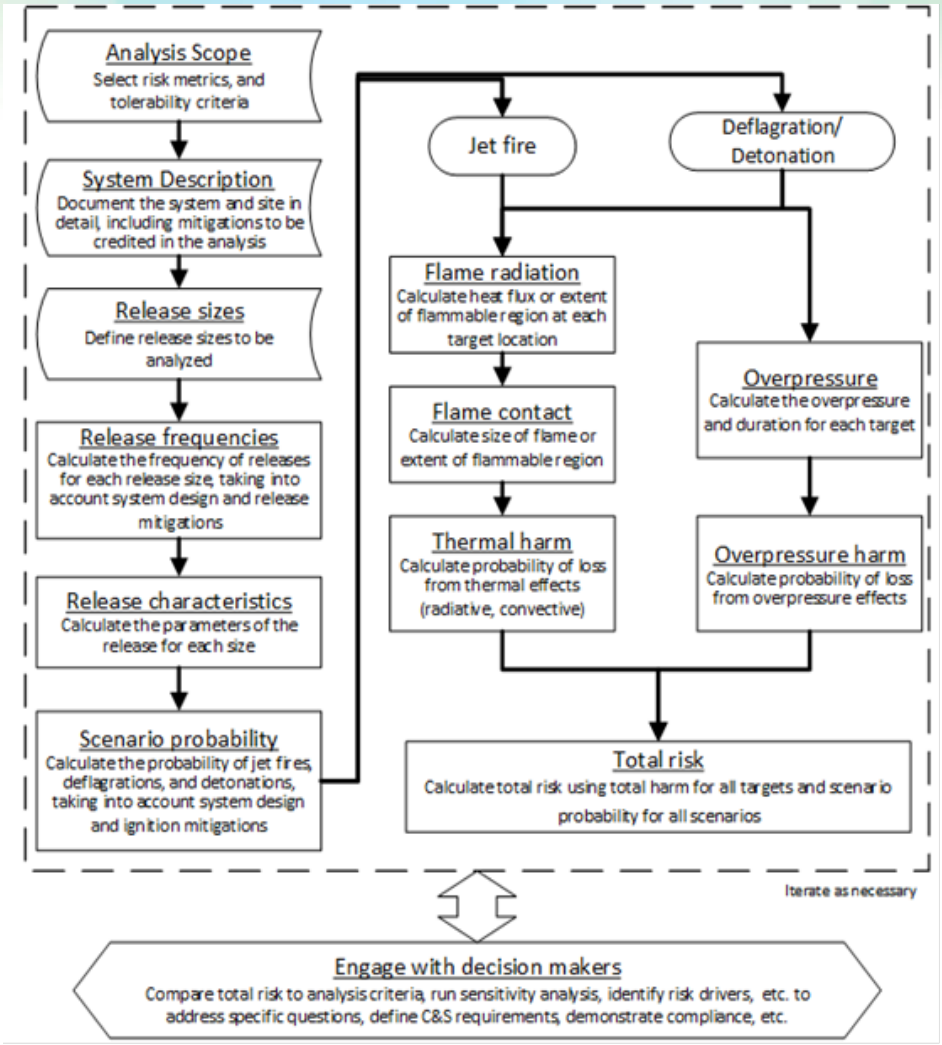
- Properties of Hydrogen
- Unignited releases: Orifice flow; Notional nozzles; Gas jet/plume; Accumulation in enclosures
- Ignited releases: Jet flames w/ and w/o buoyancy; overpressures in enclosures

Mathematics Middleware

- Unit Conversion System
- Math.NET Numerics

Documentation

- Algorithm report (SAND2015-10216)
- User guide (DRAFT/ / SAND2015-7380 R)

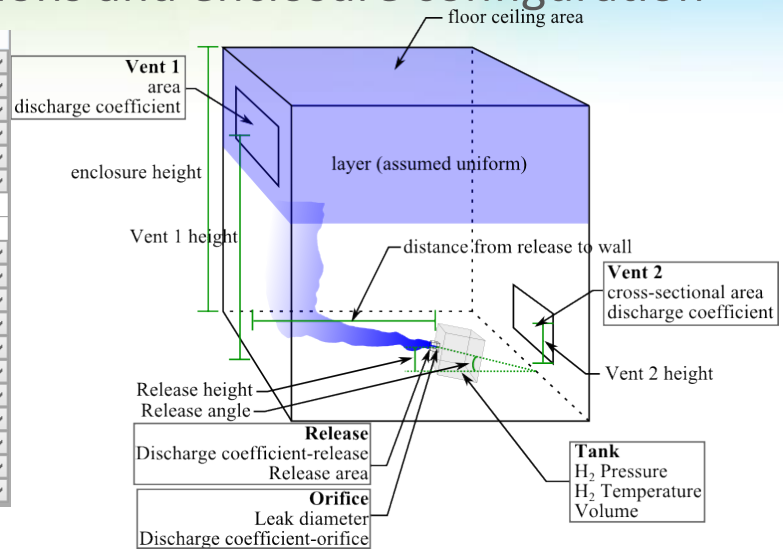


+ Free download via web

Overpressure & layer modules

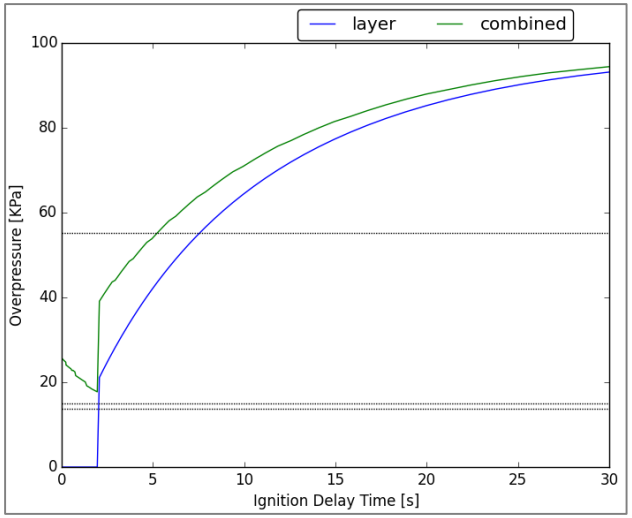
Input: Release conditions and enclosure configuration

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)

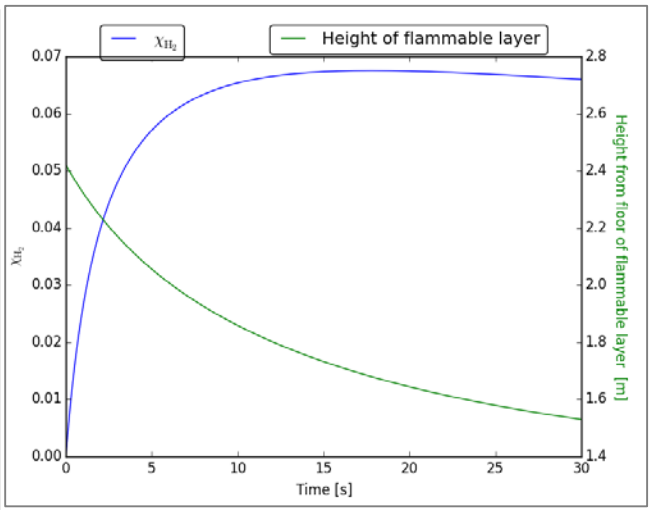


Maximum pressure (Pa): 94418.2835711473

Time this occurred (seconds): 30

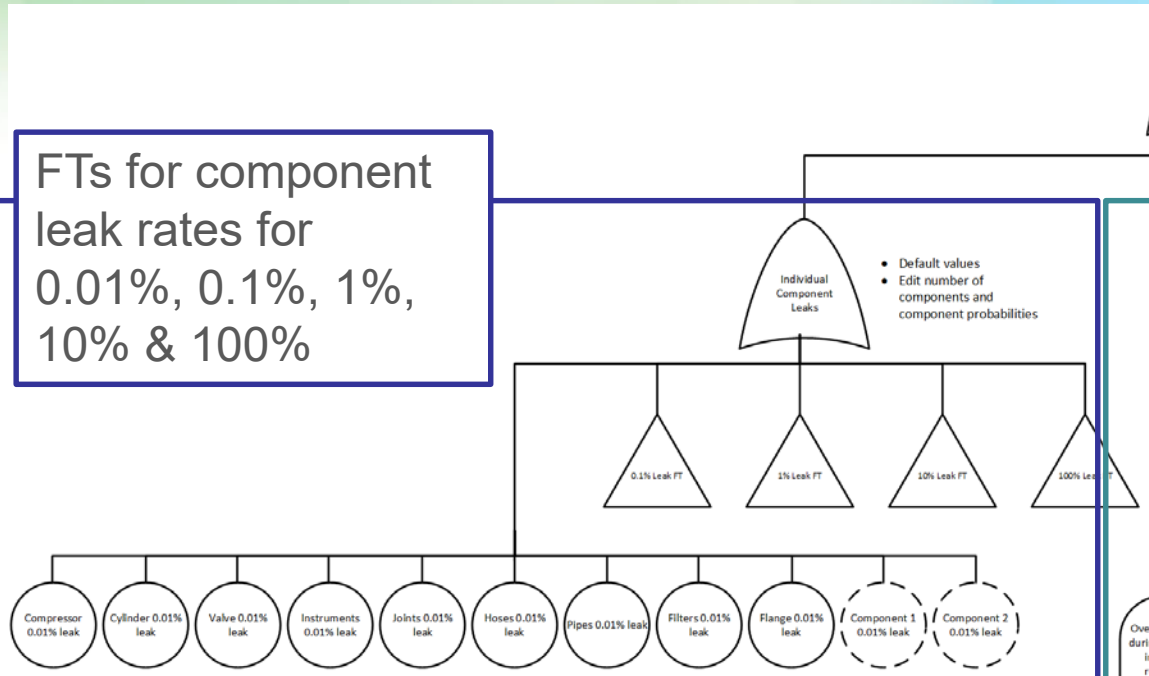
Time	Pressure
1	2.089E+004
2	2.670E+004
3	4.446E+004
4	4.957E+004
5	5.409E+004
6	5.841E+004
7	6.210E+004
8	6.528E+004
9	6.849E+004
10	7.105E+004
11	7.365E+004
12	7.595E+004
13	7.788E+004
14	7.982E+004
15	8.155E+004

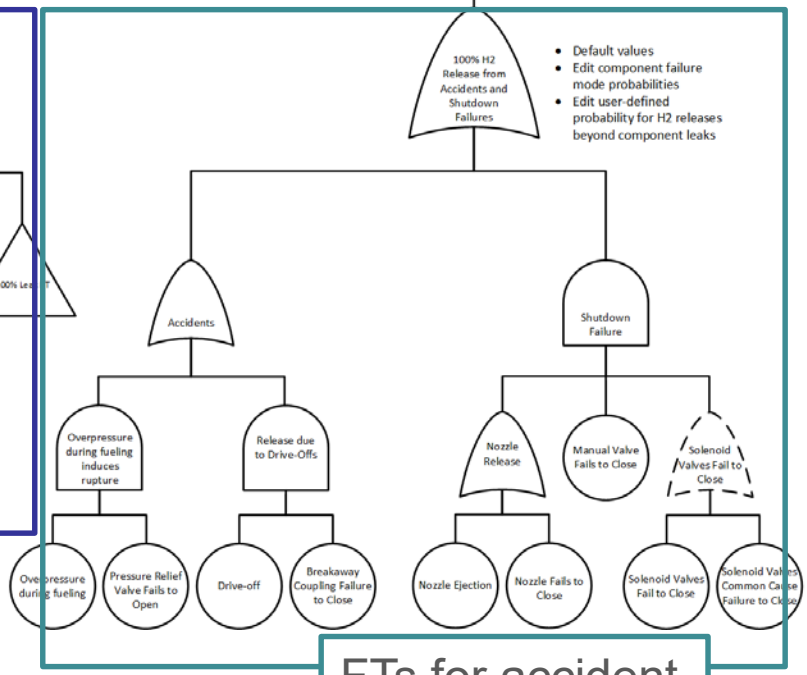
Depth	Concentration
0.39711803	2.622E-002
0.47903418	3.974E-002
0.54935446	4.791E-002
0.61057559	5.331E-002
0.66450595	5.707E-002
0.71242342	5.979E-002
0.75545507	6.181E-002
0.79417555	6.332E-002
0.82938139	6.447E-002
0.86156604	6.535E-002
0.89098494	6.601E-002
0.91810608	6.651E-002
0.94312791	6.688E-002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



QRA Fault Trees (FT) Updates

FTs for component leak rates for 0.01%, 0.1%, 1%, 10% & 100%





Current risk analysis contains static fault trees for one scenario. Customization will allow for risk analysis to be applied to unique H2 applications

FTs for accident scenarios or shutdown failures

Quantitative risk assessment (QRA) provides opportunity to accelerate development of & add rigor to RCS

- Code developers (e.g., NFPA, ISO) requiring increasingly rigorous and defensible technical basis for codes
- Increasing use of QRA within RCS over the last decade:
  - SFPE guidance issued in **2006;** NFPA in **2007**: "*Guidance Document for Incorporating Risk Concepts into NFPA Codes and Standards*"
- 3 main uses of QRA within RCS:
  1. Create a risk-informed requirement (e.g., QRA, models for safety distances)
  2. Allow risk-equivalent code compliance (e.g., performance-based design),
  3. Develop risk-based codes & regulation (e.g., Dutch RIVM approach to regulation)