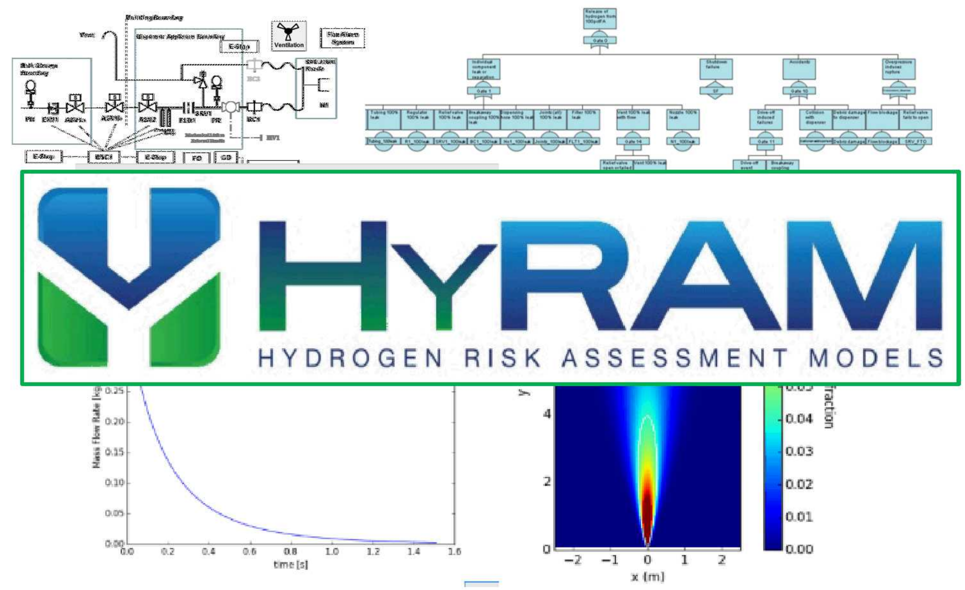
SAND2019-6572PE

Hydrogen Quantitative Risk Assessment



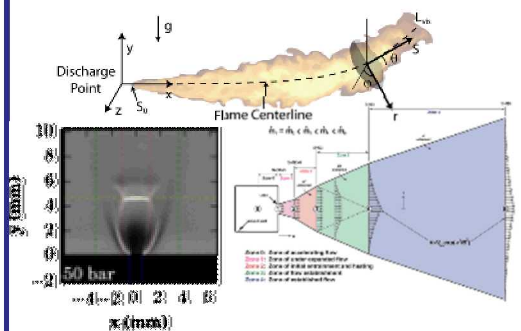
Alice B. Muna
Sandia National Laboratories

Korea Gas Safety Corporation Meeting
June 18, 2019

SAND2019-2319

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

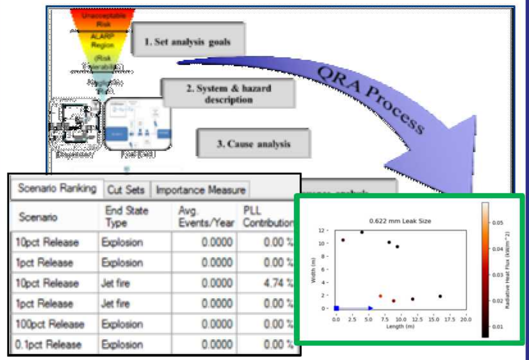
Behavior R&D



Develop and validate scientific models

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

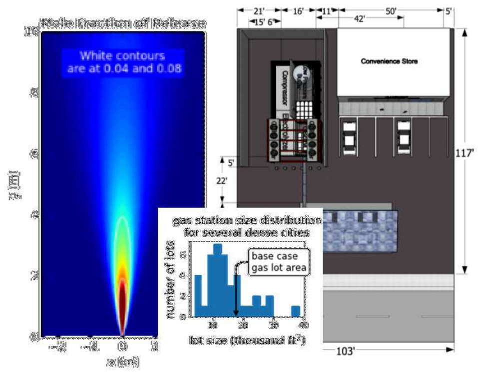
Risk R&D



Develop integrated methods and algorithms

for enabling consistent, traceable and rigorous QRA

Application in SCS

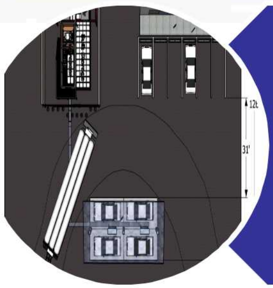


Apply QRA & behavior models to real problems

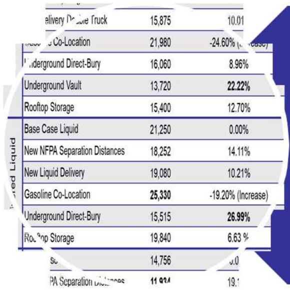
in hydrogen infrastructure and emerging technology

Developing methods, data, tools for H_2 safety & SCS

Hydrogen Codes and Standards Challenges

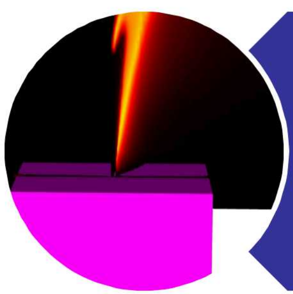


LH2 Separation Distances



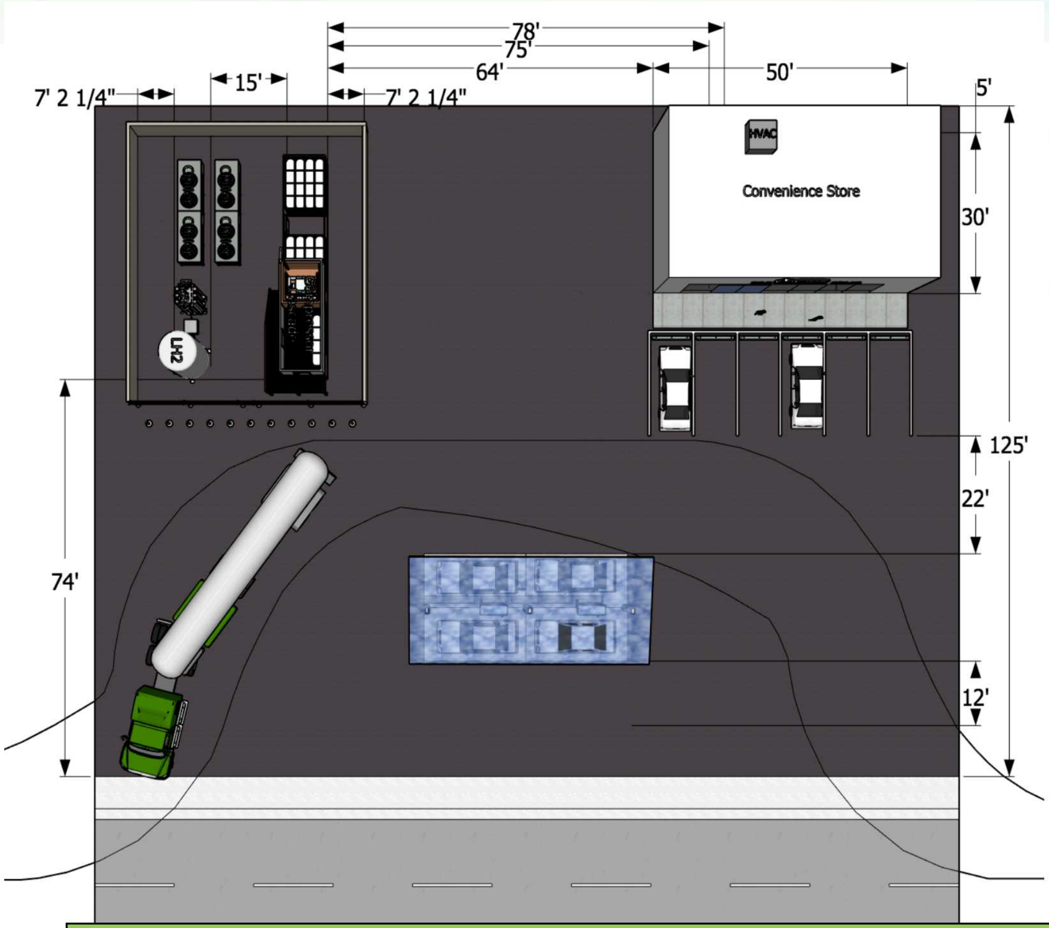
elivery Tr...e Truck	15,875	10.01
...Co-Location	21,980	-24.60%
...derground Direct-Bury	16,060	8.96%
Underground Vault	13,720	22.22%
Rooftop Storage	15,400	12.70%
Base Case Liquid	21,250	0.00%
New NFPA Separation Distances	18,252	14.11%
New Liquid Delivery	19,080	10.21%
Gasoline Co-Location	25,330	-19.20% (Increase)
Underground Direct-Bury	15,515	26.99%
Ro...op Storage	19,840	6.63 %
	14,756	
...PA Separation ...	11,9...	19....

Permitting Alternative Means



Tunnel Safety

Liquid hydrogen QRA methodology development



- Goal: Science-based <u>liquid</u> separation distances
- Progress:
  - Behavior experiments
  - LH2-specific leak frequencies in development
  - HyRAM flexibility will support liquid developments

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

Science-based liquid separation distances

- Goal: Develop leak frequencies and other data needed to support the NFPA 2/55 separation distance task group
- Progress:
  - In-person meeting held in October 2018 to determine next steps
  - Generated a leak frequency template and are working with industry partners to develop consistent set of data
  - LNG leak frequencies developed as a first step
  - LH2 release model being added to HyRAM

Specific Component Type	Severity	Frequency	Units	Leak Size Description
		Piping		
Pipe Diameter (d) < 50 mm	Rupture	1.00E-06	Per Meter Year	100% cross sectional area
d < 50 mm	Major	5.00E-06	Per Meter Year	1" (25 mm)
50 mm ≤ d < 149 mm	Rupture	5.00E-07	Per Meter Year	100% cross sectional area
50 mm ≤ d < 149 mm	Medium	2.00E-06	Per Meter Year	1" (25 mm)
150 mm ≤ d < 299 mm	Rupture	2.00E-07	Per Meter Year	100% cross sectional area
150 mm ≤ d < 299 mm	Major	4.00E-07	Per Meter Year	1/3 of pipe diameter
150 mm ≤ d < 299 mm	Minor	7.00E-07	Per Meter Year	1" (25 mm)
300 mm ≤ d < 499 mm	Rupture	7.00E-08	Per Meter Year	100% cross sectional area
300 mm ≤ d < 499 mm	Major	2.00E-07	Per Meter Year	1/3 of pipe diameter
300 mm ≤ d < 499 mm	Medium	4.00E-07	Per Meter Year	2" (50 mm)
300 mm ≤ d < 499 mm	Minor	5.00E-07	Per Meter Year	1" (25 mm)
500 mm ≤ d < 1000 mm	Rupture	2.00E-08	Per Meter Year	100% cross sectional area
500 mm ≤ d < 1000 mm	Major	1.00E-07	Per Meter Year	1/3 of pipe diameter
500 mm ≤ d < 1000 mm	Minor	2.00E-07	Per Meter Year	2" (50 mm)
500 mm ≤ d < 1000 mm	Very Small	4.00E-07	Per Meter Year	1" (25 mm)

HyRAM: Hydrogen Risk Assessment Models

First-of-its-kind integration platform for state-of-the-art hydrogen safety models & data

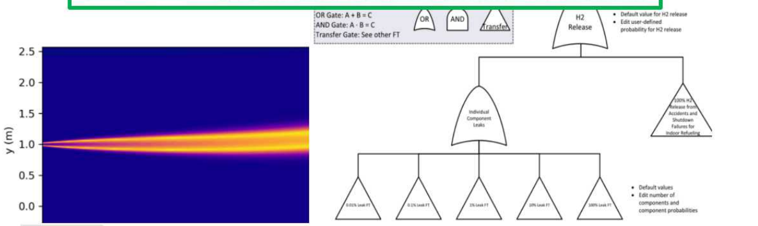
Core functionality:

- Fast-running models of hydrogen gas and flame behaviors
- Quantitative risk assessment (QRA) methodology
- Frequency & probability data for hydrogen component failures

Key features:

- Documented approach, models, algorithms
- Flexible and expandable framework; supported by active R&D
- Open source to allow external collaboration

HYRAM
HYDROGEN RISK ASSESSMENT MODELS



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

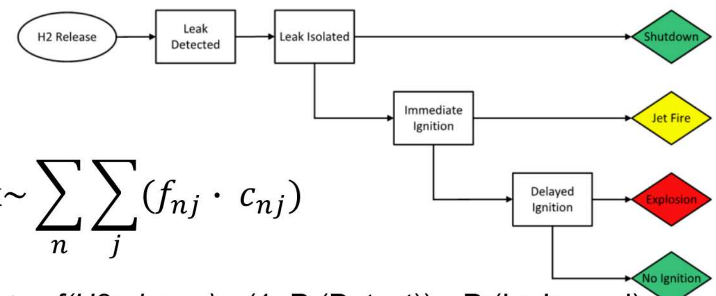
Leak Size	Mu	Sigma	Mean	Variance
0.01%	-1.7198	0.2143	1.83E-001	1.58E-003
0.10%	-3.9185	0.4841	2.23E-002	1.32E-004
1%	-5.1394	0.7898	8.01E-003	5.55E-005
10%	-8.8408	0.8381	2.06E-004	4.31E-008
100%	-11.3365	1.3689	3.04E-005	5.11E-009

Download at http://hyram.sandia.gov

HyRAM *QRA* model

Accident sequences

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



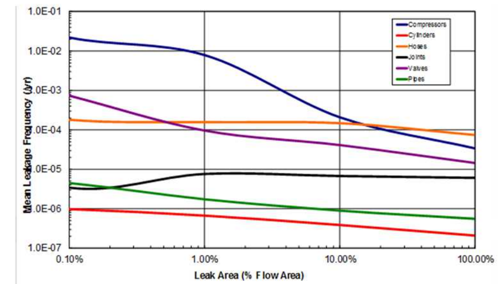
$$\text{Risk} \sim \sum_{n} \sum_{j} (f_{nj} \cdot c_{nj})$$

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

Release frequency

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

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



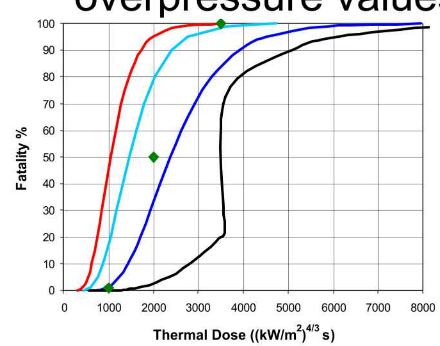
Ignition probability

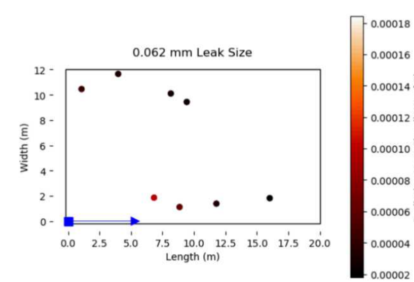
- Extrapolated from methane ignition probabilities

Hydrogen Release Rate (kg/s)	Immediate Ignition Probability	Delayed Ignition Probability
<0.125	0.0080	0.0040
0.125-6.25	0.0530	0.0270
≥6.25	0.2300	0.1200

Harm models

- Probability of fatality from exposure to heat flux, temperatures and manually entered overpressure values

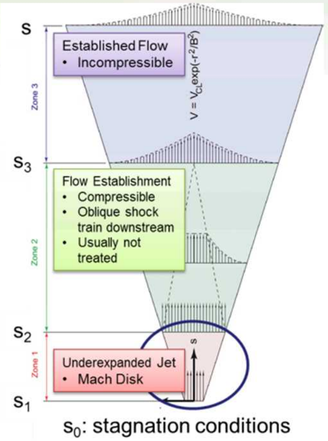


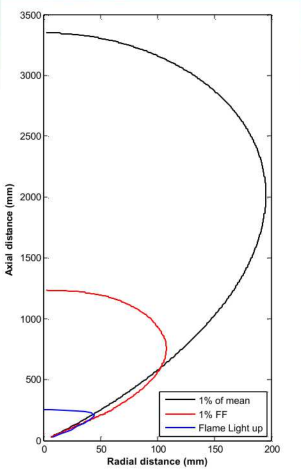


HyRAM *Behavior & Consequence models*

Release Characteristics

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



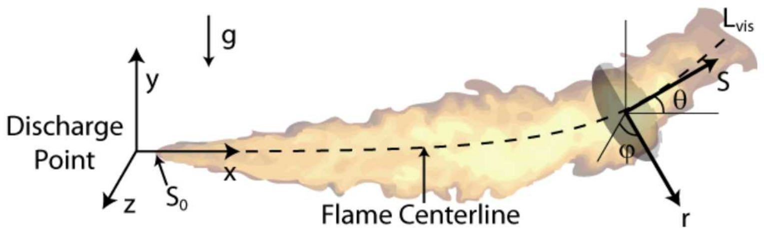


Ignition/Flame Light-up

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

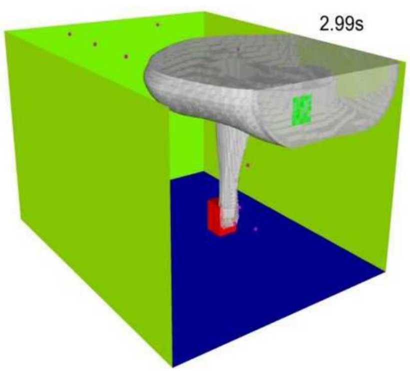
Flame Radiation

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



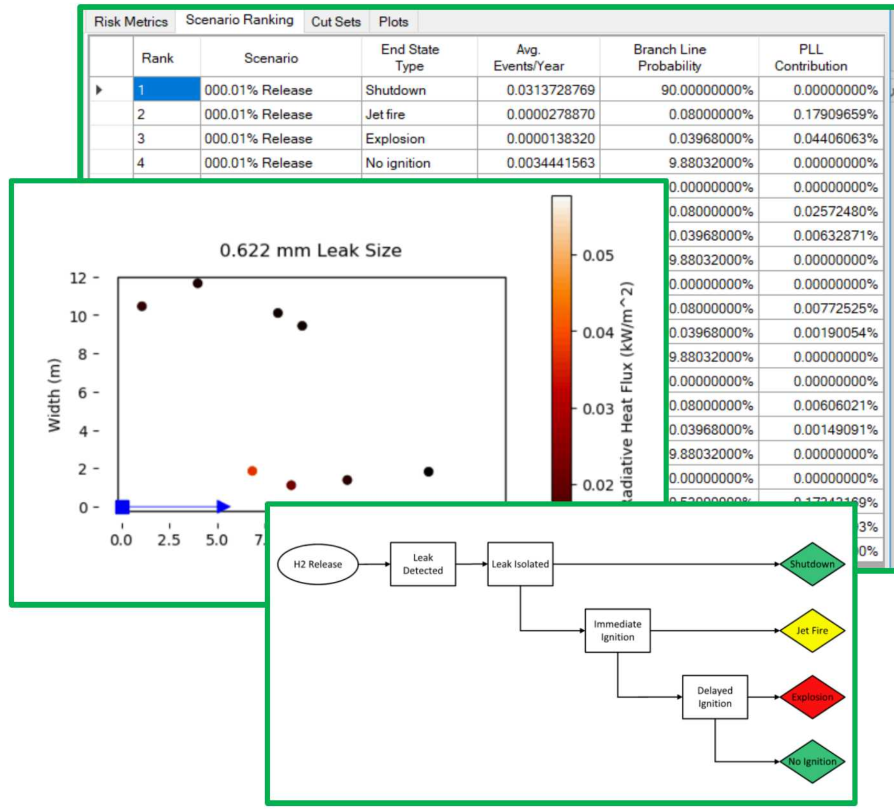
Accumulation Model

- Layer model calculates behavior for gaseous hydrogen in an enclosure
- Quantitative role of ventilation



Expanded HyRAM QRA flexibility beyond hydrogen refueling stations

- Developed additional QRA capability to enable HyRAM to be applied to a larger variety of H2 applications
  - New scenarios can be analyzed
- Open source license approved
- HyRAM 2.0 will be merged into Alternative Fuels Models (AltRAM)
  - Incorporate risk and physics models for CNG, LNG and propane
  - Open source format will support AltRAM development



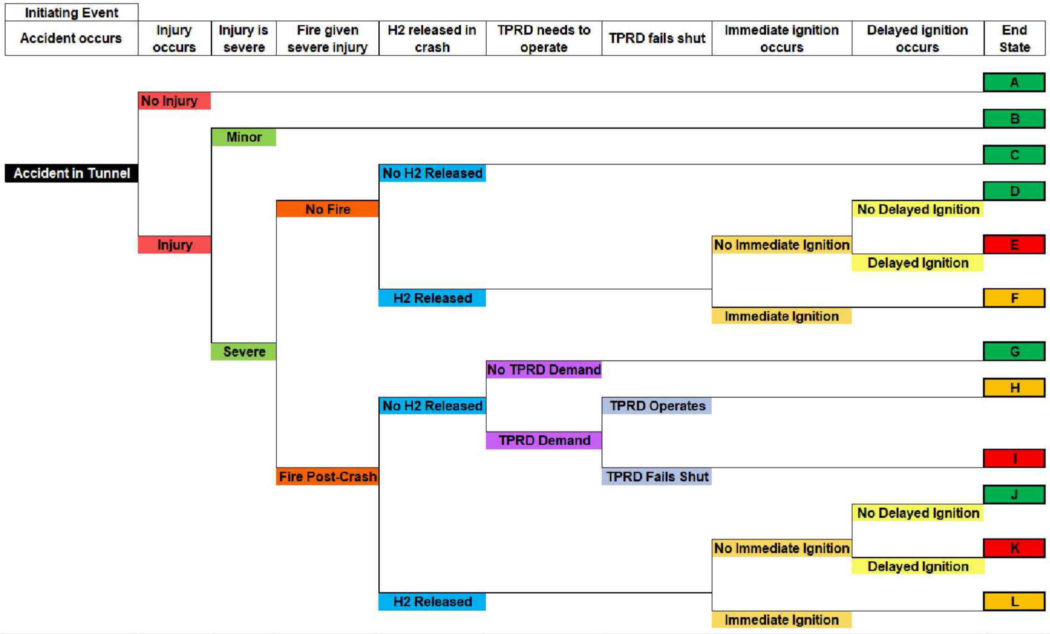
Providing HyRAM source code to larger research community will allow others to contribute to the development of HyRAM

Permitting alternative means

- Goal: Establish alternate means as a viable station permitting option with an industry partner
- Progress:
  - CRADA with industry partner (FirstElement Fuel, Inc.)
  - Drafting report documenting Alternate Means methodology
  - Report could be used for a station with separation distance challenges
  - Report will be published for larger community

Demonstrating alternate means of compliance:
- Increases options for industry in siting hydrogen fueling stations
- Overall confidence in the performance-based approach for station design

Tunnels safety study



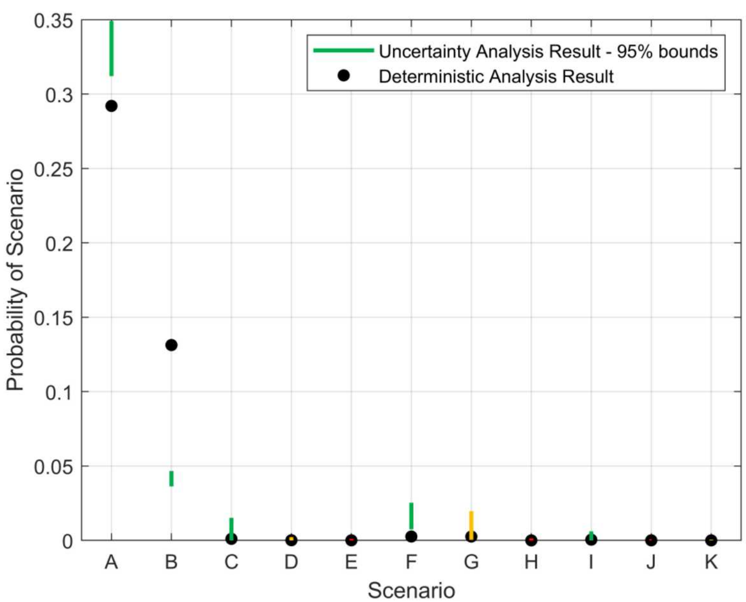
Ehrhart, Brian D., Brooks, Dusty M., Muna, Alice B., LaFleur, Chris, "Risk Assessment of Hydrogen Fuel Cell Vehicles in Tunnels," Accepted by Fire Technology Journal.

- Establishment of a joint collaboration between DOE/DOT
- IPHE RCSS initiated tunnel safety workshop with issues identified in a whitepaper
- Journal article on risk assessment of HFCV in tunnels accepted for publication
- Probabilities addressing uncertainty for different tunnel scenarios have been established

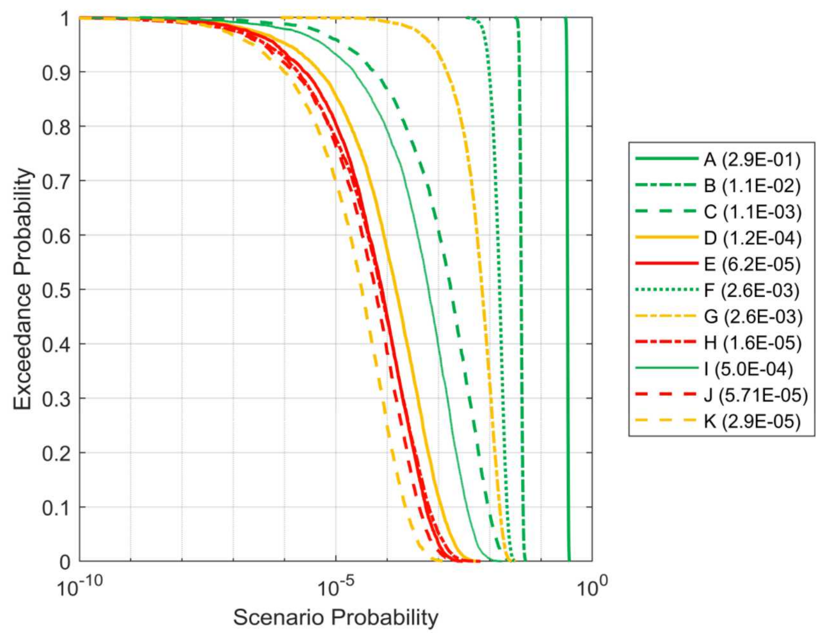
Addressing tunnels on a federal basis enables the deployment of fuel cell vehicles in other parts of the US

Calculating uncertainty around scenario probabilities

Uncertainty Quantification on Deterministic Scenario Probabilities



Complimentary Cumulative Distribution Functions: Exceedance Probability Curves



Calculation of uncertainty allows a more complete range of answers to be characterized

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
  - Consensus agreement on suitable means of quantifying hydrogen system mitigation features is not reached
- Hydrogen Tunnel Safety
  - Local AHJ permissions may not be granted, despite scientific analysis
  - Different jurisdictions grant differing permissions for FCEV, resulting in complicated use allowances

Thank you

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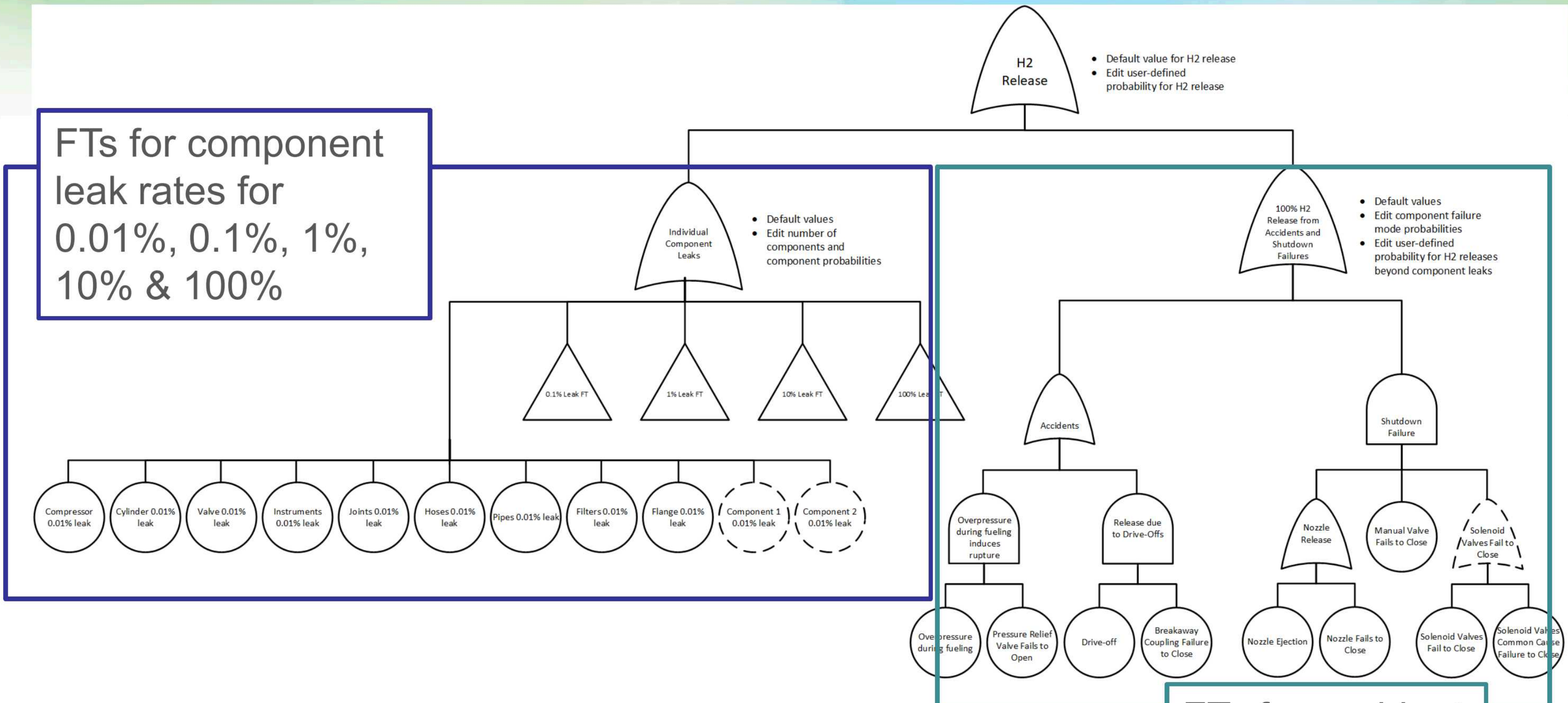
QRA Fault Trees (FT) Updates

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

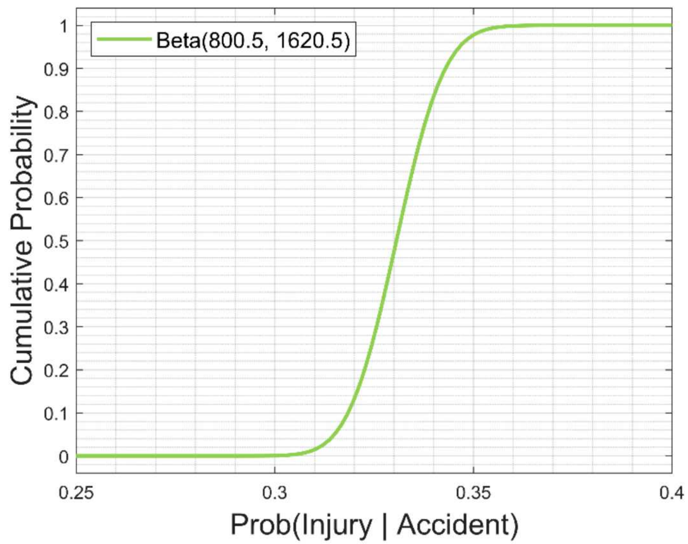


FTs for accident scenarios or shutdown failures

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

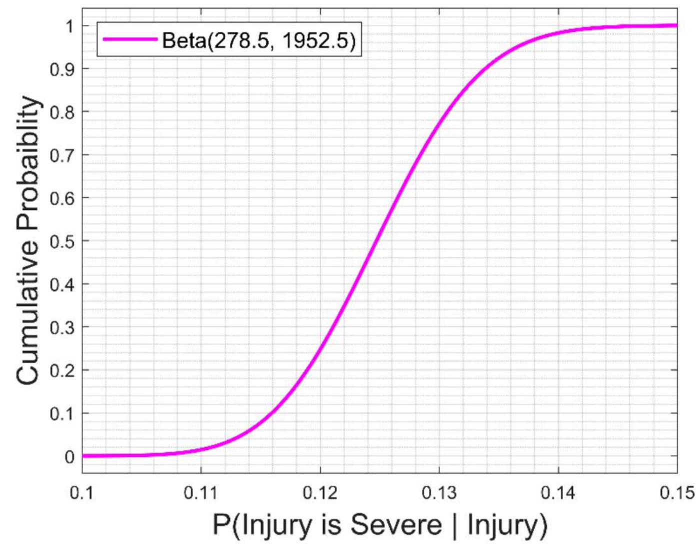
Uncertainty around scenario probabilities

Probability of injury given an accident



	Total Number of Accidents	Total Number of Injuries
Z-L Ma et al. (via Bassan)	116	35
Caliendo	2304	765

Probability that an accident is severe given that an injury occurred

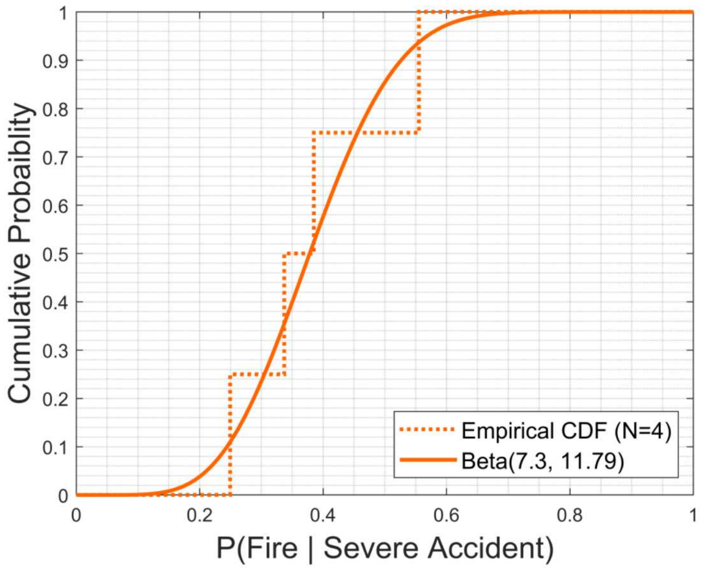


	Total Number of Injuries	Severe Injury (or fatality)
Amunsden	562	97
Amunsden	1130	125
Z-L Ma et al.	35	11
Meng Qu	503	45

Calculation of uncertainty allows a more complete range of answers to be characterized

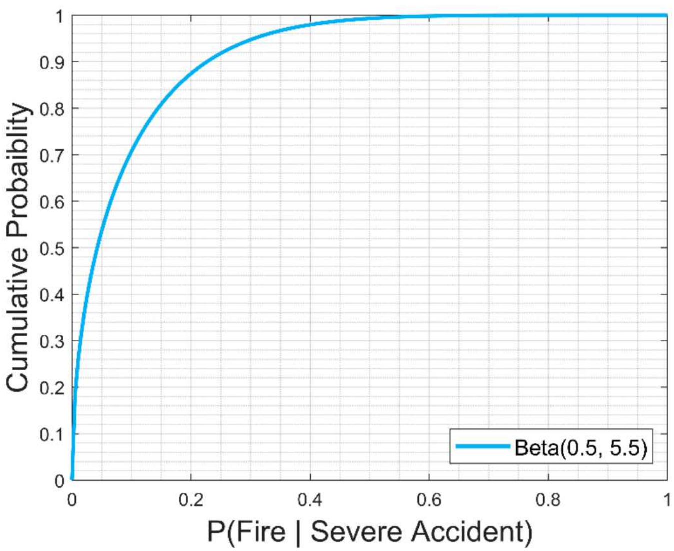
Uncertainty around scenario probabilities

Probability that a fire occurs given severe accident



Year:	2006	2007	2008	2009
Average Severe Crash Rates	0.2045	0.1608	0.0913	0.1284
Average Fire Crash Rates	0.0510	0.0619	0.0507	0.0433

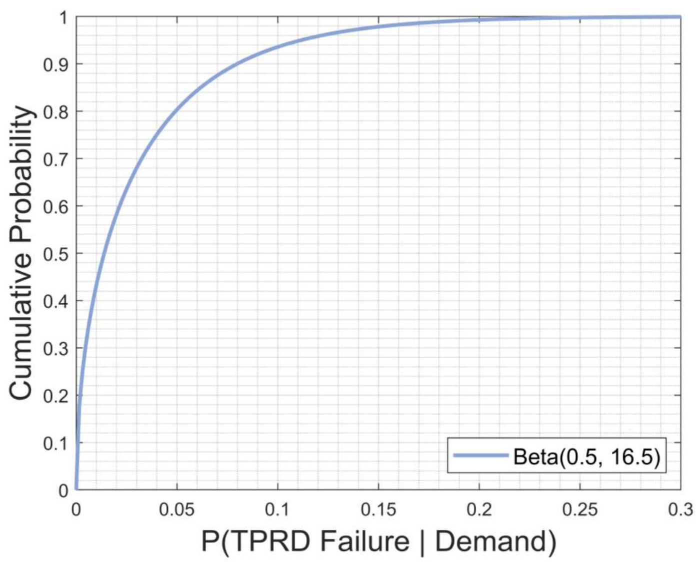
Probability of damage-induced H2 release



- Based on 5 experiments where no release occurred
- Beta distribution assumed along with Jeffrey's uninformed prior

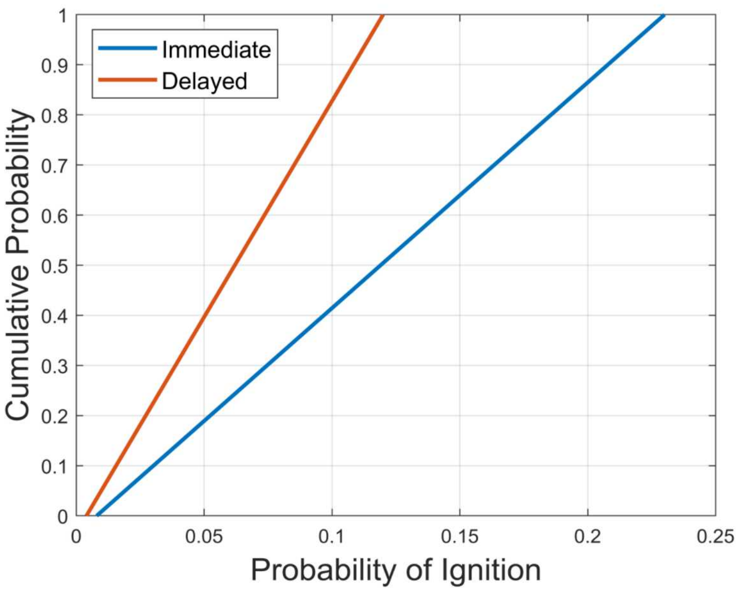
Uncertainty around scenario probabilities

Uncertainty of TPRD failure to operate



- Bayesian approach with informed prior
- Choice of an informed prior leads to a lower estimated probability of failure, but overall range where most of the distribution lies is similar to that obtained with a Jeffrey's prior

Probability of H2 ignition



- Due to wide range of ignition probability values, a uniform distribution between the lowest and highest values was chosen