Hydrogen and Fuel Cells Program

SAND2014-4169P

Hydrogen QRA & HyRAM Toolkit Introduction

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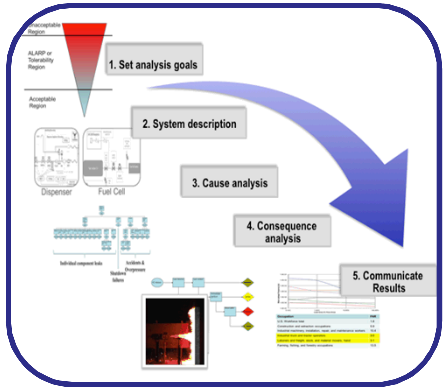
Sandia research program

Objective: Develop & demonstrate methodologies to support the use of QRA as a tool for development & revision of RCS and safety best practices.

Apply risk assessment techniques in step-out hydrogen technologies



Develop integrated algorithms for conducting QRA for H_2 facilities and vehicles

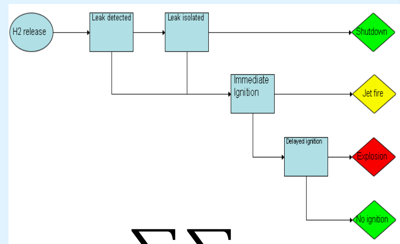
Develop and validate scientific models to provide reduced-order information for accurate depiction of releases, flames, etc.

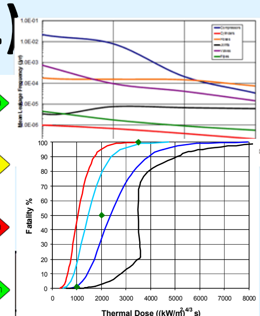
Enabling QRA tools for H2 industry

Previous SNL work: Develop the framework for doing H2 QRA: Develop, validate & integrate H2 data and models

QRA method, data & models (FY08-11)

- Hazards
- Accident sequences
- Release frequencies
- Ignition probabilities
- Harm/damage



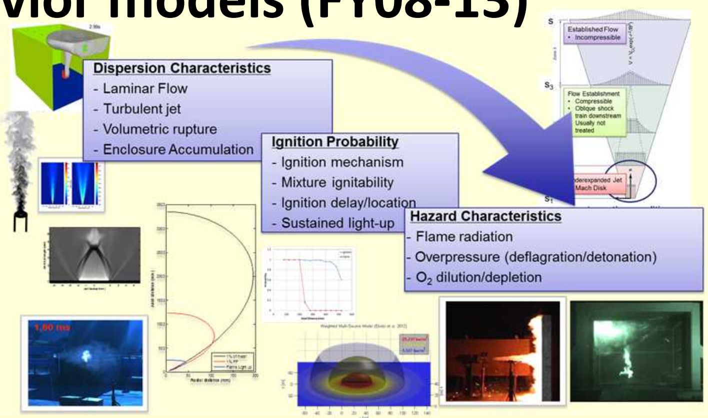


$$Risk \sim \sum_n \sum_j (f_{nj} \cdot c_{nj})$$

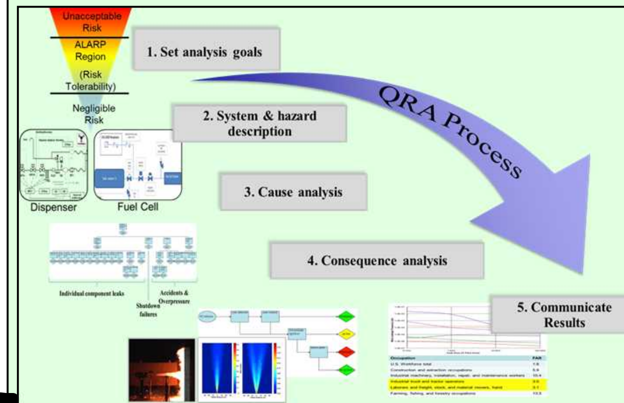
<0.125	0.008	0.004
0.125 – 6.25	0.053	0.027

Physics-based behavior models (FY08-13)

- GH2 release
- Ignition
- Reduced-order jet flame models
- Deflagration simulation



Integrated algorithm & v0 toolkit (Matlab) (FY12-13)




```
        Y=-77.1 + 6.91*log(P_s);                                    % !
    case 'Lung_HSE'                                                  % !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        %HSE - Lung hemorrhage                                        !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        Y=1.47+1.371*log(P_s);                                      % !
    case 'Head_impact'                                               % !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        %TNO - Head impact                                            !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        Y=5-8.49*log((2430./P_s)+4e8./(P_s.*impulse));              % !
    case'Collapse'                                                   % !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
```

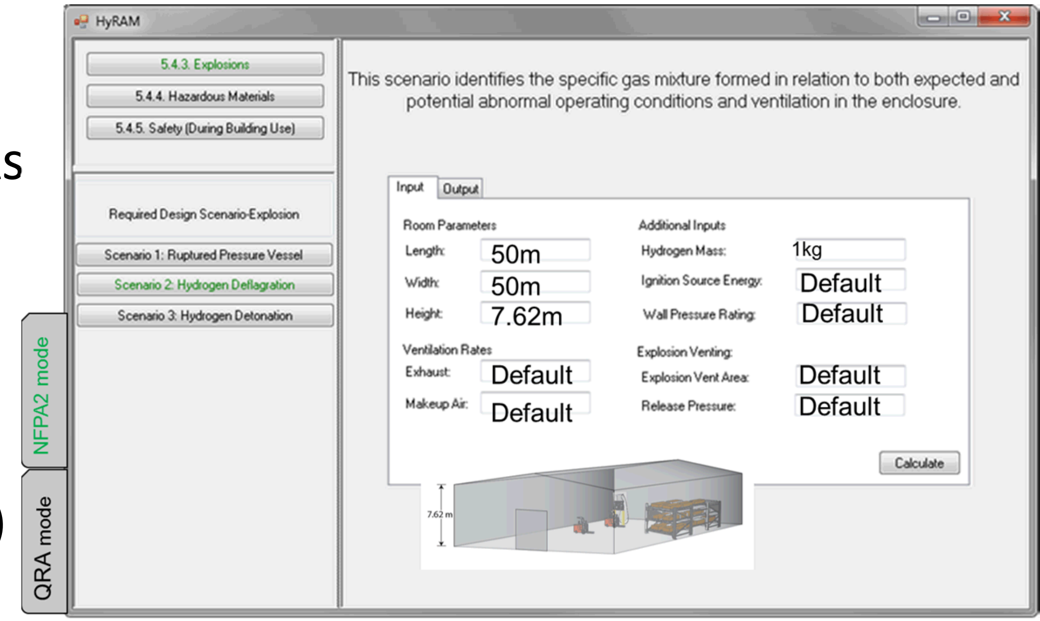
QRA-informed C&S (FY11-13)

- Indoor fueling (NFPA2 Ch. 10)
- Station separation distances (NFPA2 Ch.7)

Gaps/Needs: 1) User-friendly toolkit to enable CDO-led QRAs, industry-led PBD siting option 2) Reduced-order deflagration models 3) downstream jet flame physics 4) Models for LH2 releases

HyRAM = Hydrogen Risk Assessment Models

- **Goal**: Develop toolkit to enable integrated probabilistic and deterministic models for H2 QRAs
  - All relevant hazards (thermal, mechanical, toxicity)
  - Probabilistic models & data
  - H2 phenomena (gas release, ignition, heat flux, overpressure)



- Windows GUIs, planning HTML interface
- Three planned interfaces (views):
  - **“QRA mode”**
  - **“NFPA2 mode”**
  - “Standalone physics mode”

First-of-its-kind software tool for integrating H2 consequence models w/ QRA models

Outline

- Risk assessment overview
- Risk metrics & hazards
- HyRAM Toolkit demo (interactive)

What is Risk Assessment?

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

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

Can be <u>qualitative</u> or <u>quantitative.</u>

Quantitative form referred to as QRA (Quantitative Risk Assessment)

Risk Assessment for NFPA C&S (based on SFPE)

- SFPE & NFPA provide guidance for using risk assessment for C&S development and performance-based design and compliance:
  - *SFPE Engineering Guide to Fire Risk Assessment* (2006)
  - Rose (2007) *Guidance Document for Incorporating Risk Concepts into NFPA Codes and Standards*
  - Guides do not require a particular analysis method, tool, analysis goal, criteria, etc.
- **Caution: "Risk Assessment" is a generic term!**
  - Encompasses a range of qualitative and quantitative techniques, conducted for a range of purposes, in a range of industries.

Quality can vary widely

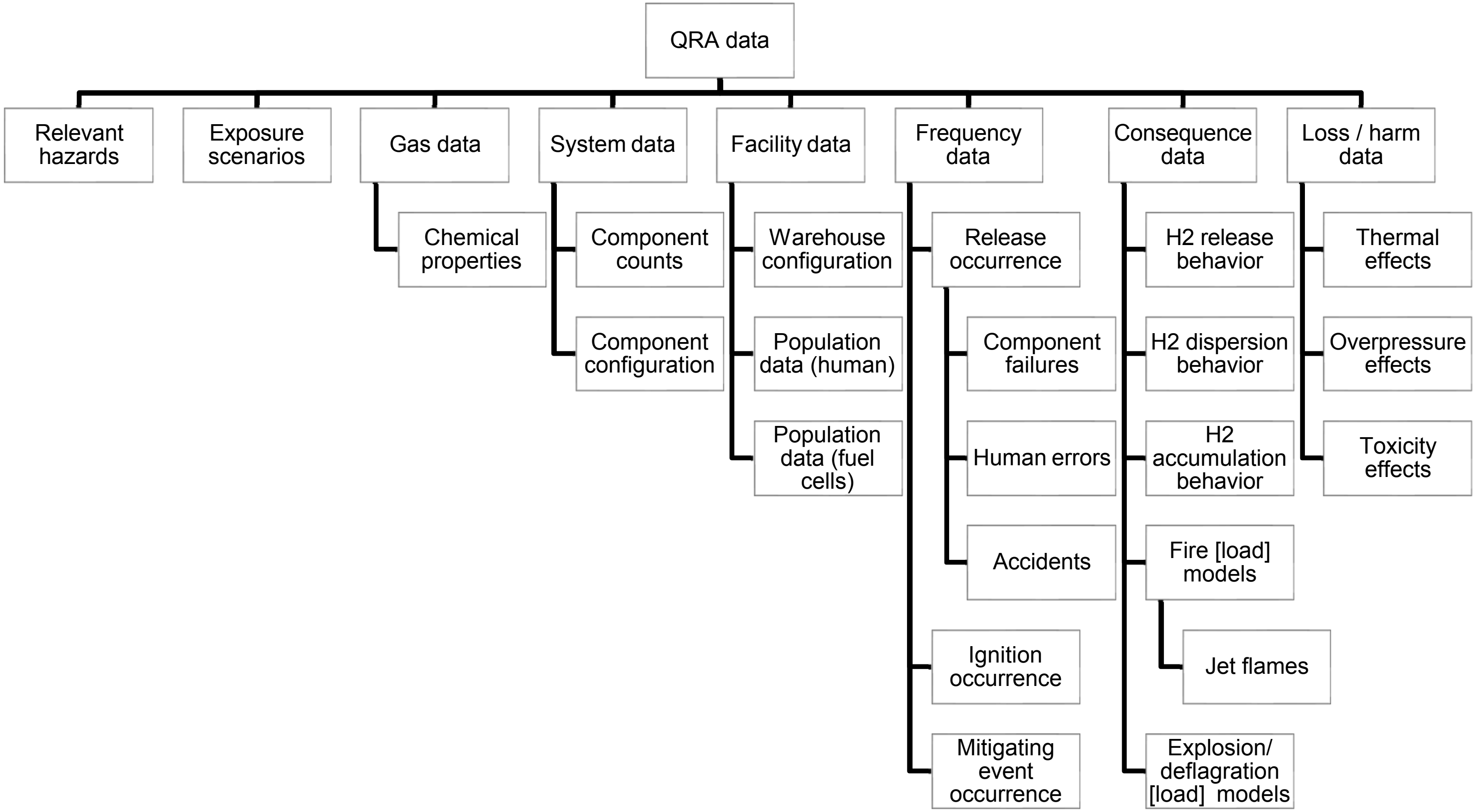
- SFPE & NFPA provide guidance for using risk assessment for C&S, **not a standard method for doing risk assessment, or standard criteria**

- Downside of this flexibility: Quality of assessment can vary widely based on analysis team, methodology used, quality of data, fidelity and appropriateness of underlying models, etc.
  - It is very difficult to evaluate the quality of an analysis, the appropriateness of the model, the correct implementation of the model, the comprehensiveness of the model without extensive knowledge of every piece of the QRA model.
  - Quality is extremely important for developing consensus for RCS developers

How do other regulators promote quality?

- Some regulators:
  - Require use of QRA instead of qualitative approaches
  - Require a particular QRA method and particular set of models (or software package)
  - Require specific analysis parameters and/or data
  - Define specific analysis criteria

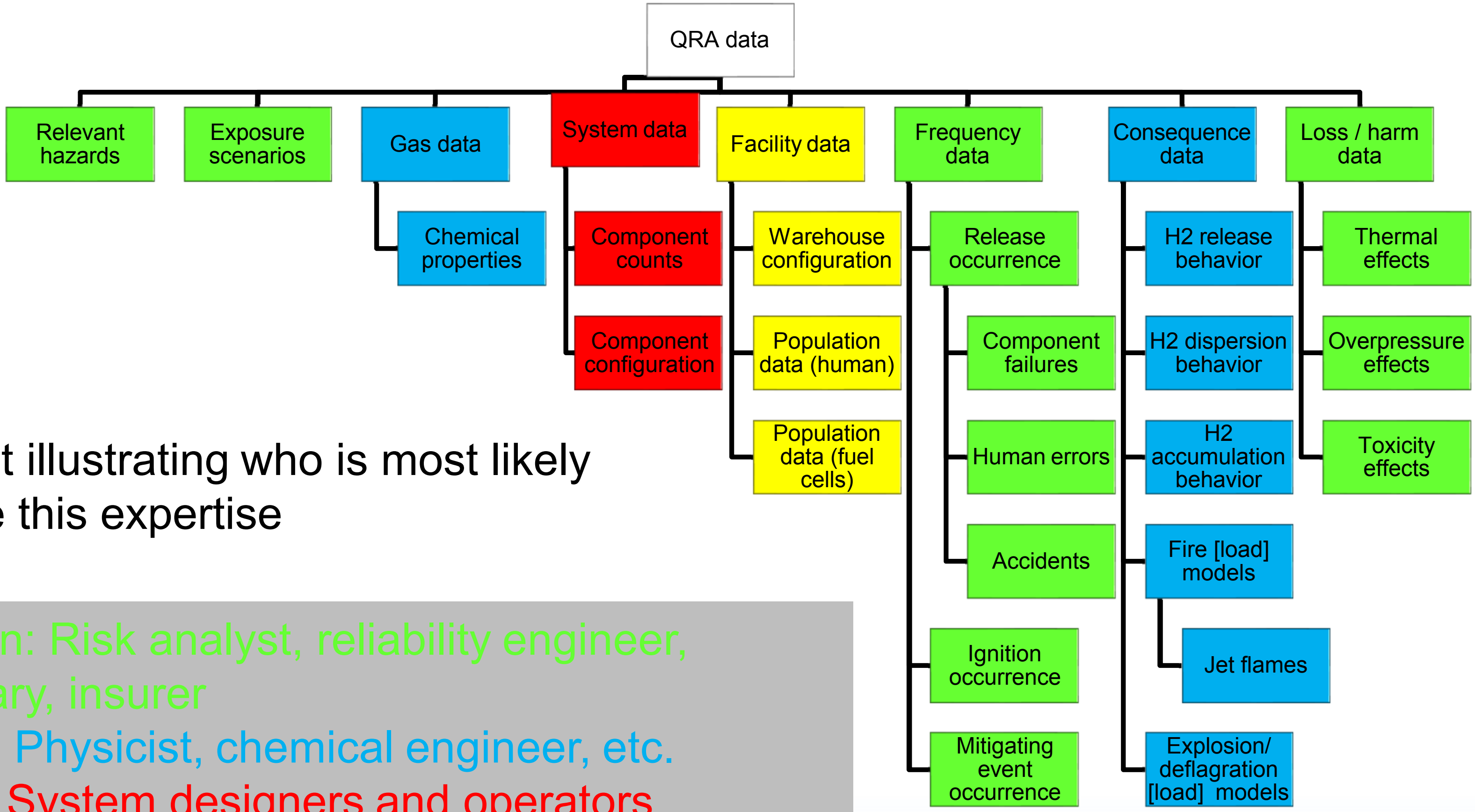
A quality QRA incorporates a large body of information



It is non-trivial to…

- Find best-available models & data for all of these pieces
- And combine those all into a single framework
- …And still work your day job

Challenge: No one is an expert in all of this (not even Sandia)

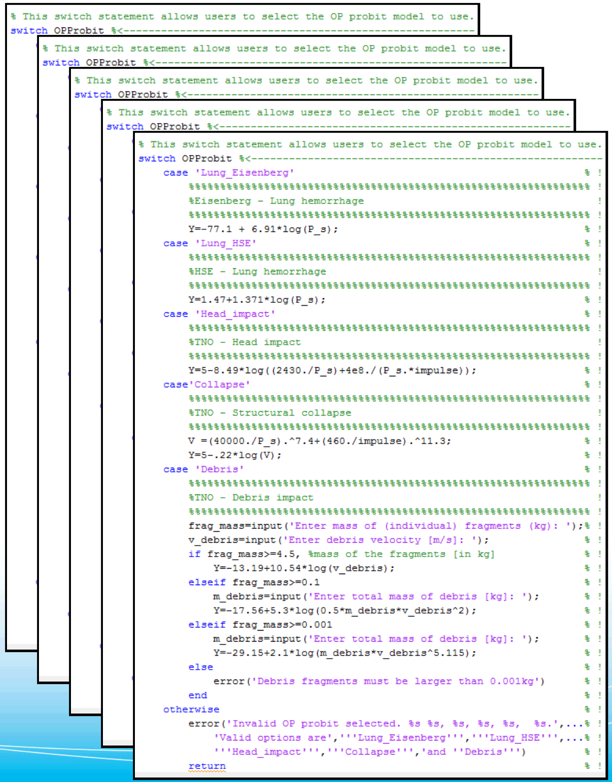


WAG at illustrating who is most likely to have this expertise

Green: Risk analyst, reliability engineer, actuary, insurer
Blue: Physicist, chemical engineer, etc.
Red: System designers and operators
Yellow: Facility designer, fire marshall

Predecessor to HyRAM: Indoor Fueling QRA algorithm

- Needed integrated algorithm to perform QRA for indoor fueling (NFPA2, Ch. 10).
- Unfortunately, no tool exists for conducting such analysis
  - Current commercial QRA tools do not have validated physics models for hydrogen, or data for hydrogen systems.
- Algorithms written in Matlab (20+scripts, 100+inputs, No GUI)
  - Full code in SAND2012-10150
  - Based on methods/data used for separation distances, plus additional information
  - User profile: Sandia risk analyst familiar with Matlab, conducting QRA with integrated behavior models, for NFPA2 Ch. 10 revisions. *Read: Katrina Groth*



```
% This switch statement allows users to select the OP probit model to use.
switch OPProbit %<-----------------------------------------------------------
    case 'Lung_Eisenberg'                                              % !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        %Eisenberg - Lung hemorrhage                                      !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        Y=-77.1 + 6.91*log(P_s);                                       % !
    case 'Lung_HSE'                                                    % !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        %HSE - Lung hemorrhage                                            !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        Y=1.47+1.371*log(P_s);                                         % !
    case 'Head_impact'                                                 % !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        %TNO - Head impact                                                !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        Y=5-8.49*log((2430./P_s)+4e8./(P_s.*impulse));                 % !
    case'Collapse'                                                     % !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        %TNO - Structural collapse                                        !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        V =(40000./P_s).^7.4+(460./impulse).^11.3;                     % !
        Y=5-.22*log(V);                                                % !
    case 'Debris'                                                      % !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        %TNO - Debris impact                                              !
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% !
        frag_mass=input('Enter mass of (individual) fragments (kg): ');% !
        v_debris=input('Enter debris velocity [m/s]: ');               % !
        if frag_mass>=4.5, %mass of the fragments [in kg]              % !
            Y=-13.19+10.54*log(v_debris);                              % !
        elseif frag_mass>=0.1                                          % !
            m_debris=input('Enter total mass of debris [kg]: ');       % !
            Y=-17.56+5.3*log(0.5*m_debris*v_debris^2);                 % !
        elseif frag_mass>=0.001                                        % !
            m_debris=input('Enter total mass of debris [kg]: ');       % !
            Y=-29.15+2.1*log(m_debris*v_debris^5.115);                 % !
        else                                                           % !
            error('Debris fragments must be larger than 0.001kg')      % !
        end                                                            % !
    otherwise                                                          % !
        error('Invalid OP probit selected. %s %s, %s, %s, %s,  %s.',...% !
            'Valid options are','''Lung_Eisenberg''','''Lung_HSE''',...% !
            '''Head_impact''','''Collapse''','and ''Debris''')         % !
        return                                                         % !
```

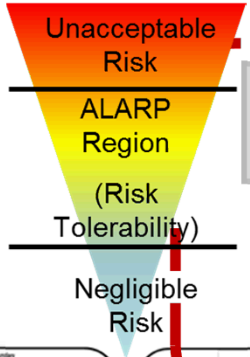
Purpose of HyRAM

- **Objective**: Facilitate H2 industry access to QRA & behavior models to enable industry-lead QRA activities, safety analyses, etc.
  - **Graphical interface** and default/generic assumptions to enable fast, high-level insights (by qualified engineers)
  - **Flexibility** to meet a variety of user goals:
    - Implement QRA and behavior models (alone or together)
    - Station siting using NFPA 2, Ch.5 (And revisions to Ch. 5)
    - Other uses: Get generic insight into: System /facility design, insurability, code revisions
  - **Initial targeted users (QRA mode)**: 2 person team -- risk analyst/engineer plus decision-maker (AHJ, C&S developer, station designer, insurer)
    - Knowledge of QRA assumptions, limitations, interpretation, presentation, neutrality
    - Must interface with decision maker to establish goals of analysis, etc.
    - Must be able to describe the system to appropriate level of detail for the application (e.g., details of design, operations, layout, maintenance)

Outline

- Risk assessment overview
- Risk metrics & hazards
- HyRAM Toolkit demo (interactive)

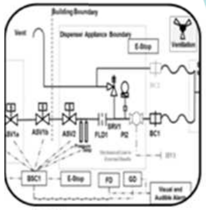
QRA Process Overview



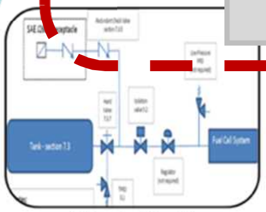
Before the Toolkit

1. Set analysis goals

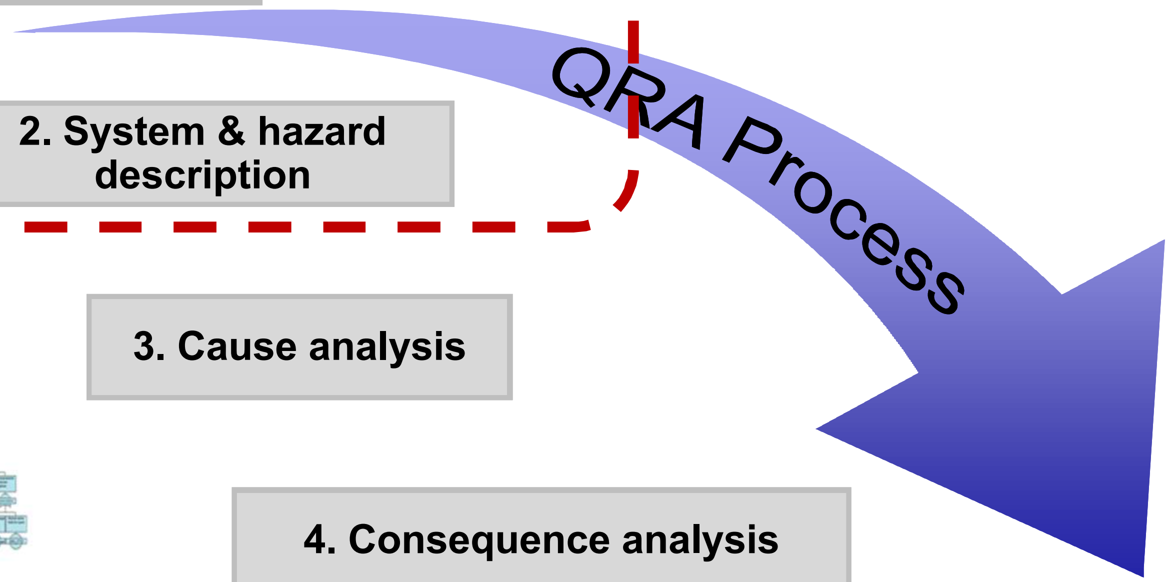
2. System & hazard description



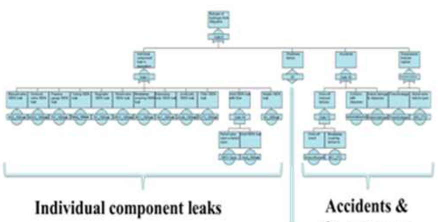
Dispenser



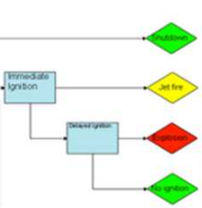
Fuel Cell

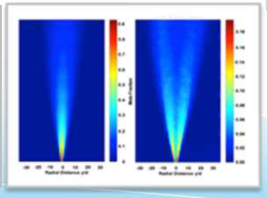


3. Cause analysis

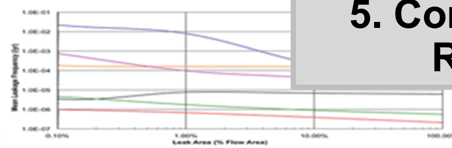


4. Consequence analysis





5. Communicate Results



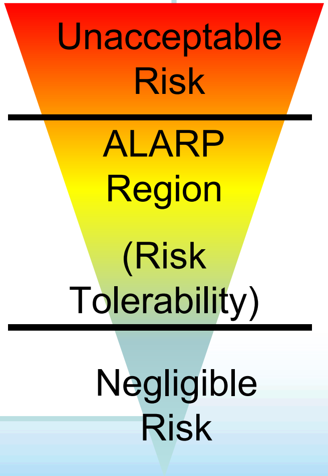
Occupation	FAR
U.S. Workforce total	1.8
Construction and extraction occupations	5.9
Industrial machinery, installation, repair, and maintenance workers	10.4
Industrial truck and tractor operators	3.0
Laborers and freight, stock, and material movers, hand	3.1
Farming, fishing, and forestry occupations	13.5

Step 1: Analysis goals (Define your metric(s))

- What type of risk assessment are you doing?
- What is the end goal?

Risk of What?	In terms of what?

• Human fatalities Individual or group?
  • Workers? Public? Adults? Children?
• Injuries
• Economic losses
• Environmental damage
• Property damage
• Cultural loss
• Business interruption...
	• Number
	  • Expectation or distribution?
	• Rate
	• Value
	• Etc.



Types of harm/loss relevant for fire safety (per NFPA)

- Life safety (public and worker)
- Property protection
- Continuity of Operations
- Environmental Protection
- Preservation of Cultural Heritage
- Preservation of National Security

SPFE (NFPA) metrics for life safety

"Examples of Life Safety metrics include:

- Death or injury rate due to fire per year
- Deaths per million people in the overall population
- Deaths per million members of a specific vulnerable or sensitive population (e.g., children)
- Deaths per building for a particular building use of occupancy type, or a change of no more than (or at least) X deaths and Y injuries per year.
- Deaths per hour spent in a facility
- Deaths within versus outside of room of fire origin
- Deaths by smoke inhalation, carbon monoxide, oxygen deprivation, toxic substances of any type, elevated temperature, or thermal radiation
- Deaths by month of year, day of week, or time of day
- Frequency in one year of fires for which time required for safe egress exceeds time available for safe egress for *X*% of occupants
- Frequency in one year of fires with more than *X* deaths." (SFPE FRA 5.2.1.2)

Rose (2007) *Guidance Document for Incorporating Risk Concepts into NFPA Codes and Standards*

SPFE (NFPA) metrics for business risk

"Continuity of operations metrics may be stated directly in terms of downtime, or more usefully, in terms of the value or impact of the interruption. Candidate measures include the following:

- downtime from fire per fire or per year
- downtime relative to a defined maximum threshold, such as an unacceptable period of loss of business
- replacement or recovery time from fire
- monetary value of business interruption
- lost days of operation
- lost value of business interruption
- value of business interruption expressed as percent of total insured value." (SFPE FRA 5.2.3.3)

"Factors to consider include the following:

- value of facility (e.g., building or buildings, including how valued, replacement cost, and replacement time)
- value of operations equipment (including how valued, replacement cost, and replacement time)
- value of stored material (including how valued and by whom)
- loss impact in terms of material worth (e.g., replacement cost)
- impact of loss on supply chain (e.g., replacement time, end product cost, revenue, net revenue over cost, profit, seasonal factors affecting production)
- loss impact of potential changes in market perception (e.g., reliability, continued service)
- rental costs (e.g., building, equipment, supplies)." (SFPE FRA 5.2.3.4)

Rose (2007) *Guidance Document for Incorporating Risk Concepts into NFPA Codes and Standards*

SPFE (NFPA) metrics for property protection

"Property protection metrics can be defined in financial terms, typically using overall values. Adjustments may be used to focus on parts of the loss, such as total fire loss exceeding insurance deductibles or total fire loss exceeding insurance coverage. Financial metrics include the following:

- monetary value of property damage per year from all fires or per fire
- monetary replacement value of property damage
- loss as percent of total insured value
- loss per fire or per year related to an anticipated maximum threshold, such as maximum foreseeable loss. "(SFPE FRA 5.2.2.3)

"Property protection objectives may also be defined in spatial rather than financial terms, such as limiting the spread of fire to a defined area relative to its point of origin. It is also acceptable to first establish a monetary value for total acceptable loss (in financial terms) and then work backwards to determine the maximum acceptable fire size, based on estimates of value per unit area and percent of value lost if damaged by fire. Spatial measures include the following:

- Area damaged
- Number of rooms damaged
- Number of floors damaged
- Number of buildings damaged
- Damage confined to object, area, room, compartment, floor, or building of origin. " (SFPE FRA 5.2.2.4)

Rose (2007) *Guidance Document for Incorporating Risk Concepts into NFPA Codes and Standards*

Example: Analysis Approach for Indoor Fueling

- **Risk metric:** FAR (Fatal Accident Rate) for workers in building
  - Expected # of fatalities per 100million exposed hours

$$FAR = \frac{PLL \cdot 10^8}{Exposed\ hours} = \frac{\sum_j (f_j \cdot c_j) \cdot 10^8}{N_{staff} \cdot 8760}$$

- **Output**: Compare predicted FAR to U.S. Bureau of Labor statistics FARs for similar occupations

Occupation	FAR
U.S. Workforce total	1.8
Construction and extraction occupations	5.9
Industrial machinery, installation, repair, and maintenance workers	10.4
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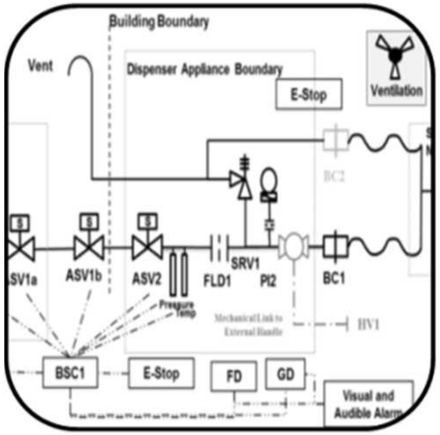
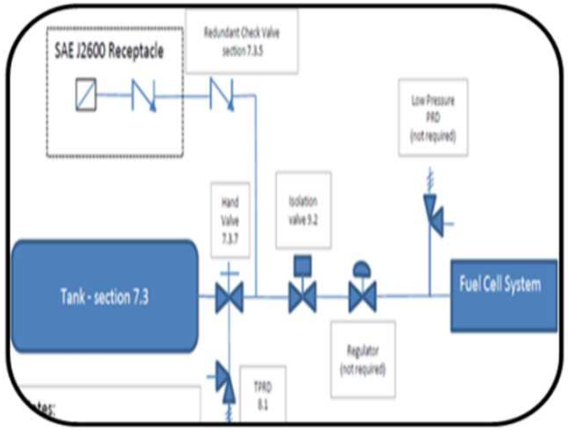
Step 2 Example: Indoor Fueling System description



Dispenser

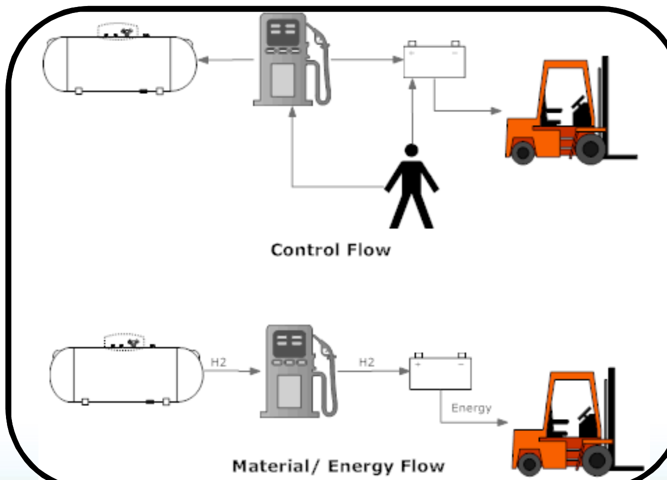


Fuel Cell

Vehicle

- Dispensing rate: 0.5kg/min
- Pressure from cascade storage: 6000psig
- Dispensing pressure: 5000psig
- Operating temperature: 70F
- 20 vehicles in the fleet
- Each vehicle holds 1kg GH_2.
- Total refueling events: 10000 fuelings/yr

Parameters



Flow diagrams

Hazard identification

- Hazard: "A condition or physical situation with a potential for harm" (SFPE) [or loss]
  - What *could* go wrong?
  - …And which ones are you including in the risk analysis?

What are the hazards?	How do they manifest?
• Mechanical • Thermal • Chemical • Electrical • Biological • Radiation • Digital • Etc.	• Pressure? Impacts? • Fire? Freezing? • Corrosion? Oxidation? • … • Bacteria, virus, plant? • ..

For a GH2 dispenser, what are the physical effect [hazards] that cause harm?)

- Mechanical:
  - Effects of overpressure (direct or indirect)
  - Impact from debris/projectiles
- Thermal*
  - Heat flux (from various types of fires, and smoke)
- Chemical
  - Toxicity/tenability (asphyxiation (From H2 or from smoke))

*[Freezing from LH2 falls into this category]

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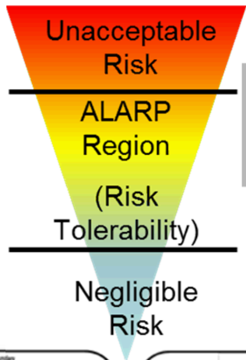
QRA Process Overview



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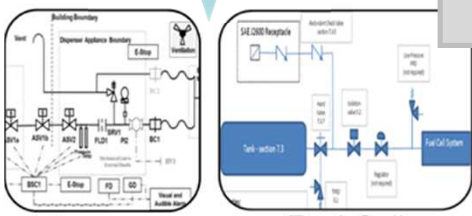
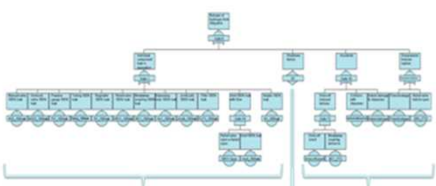


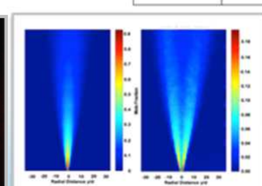
QRA Process

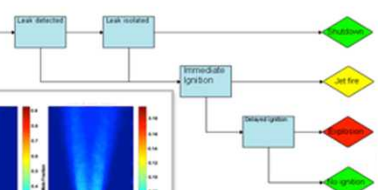
Focus of Toolkit

3. Cause analysis

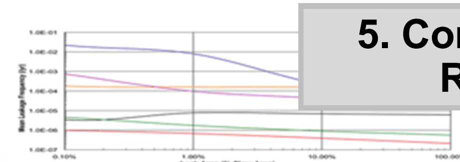
4. Consequence analysis







5. Communicate Results



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User profile for QRA mode (TBD for NFPA mode)

- Familiarity with QRA
  - Knowledge of QRA assumptions, limitations, interpretation
  - Ability to program Fault Trees (FTs)
  - Ability to post-process results for the decision-maker
- Access to system and C&S experts
  - Reminder: QRA is a team activity!
  - Must be able to describe the system to appropriate level of detail (including details of design, operations, layout, maintenance)
  - Must interface with C&S experts to help establish purpose of analysis, etc.

Risk metrics [currently] supported in HyRAM

Code designed to output 3 risk metrics:

- **FAR (Fatal Accident Rate)**
  - Expected number of fatalities per 100million exposed hours
- **AIR (Average Individual Risk)**
  - Expected number of fatalities per exposed individual
- **PLL (Potential Loss of Life)**
  - Expected number of fatalities per dispenser-year.

Also calculates expected number of:

- Leaks / releases (per dispenser-year)
- Jet fires (per dispenser-year)
- Explosions (per dispenser-year)
- Human fatalities (per dispenser-year, per worker-year, & per working hour)

And:

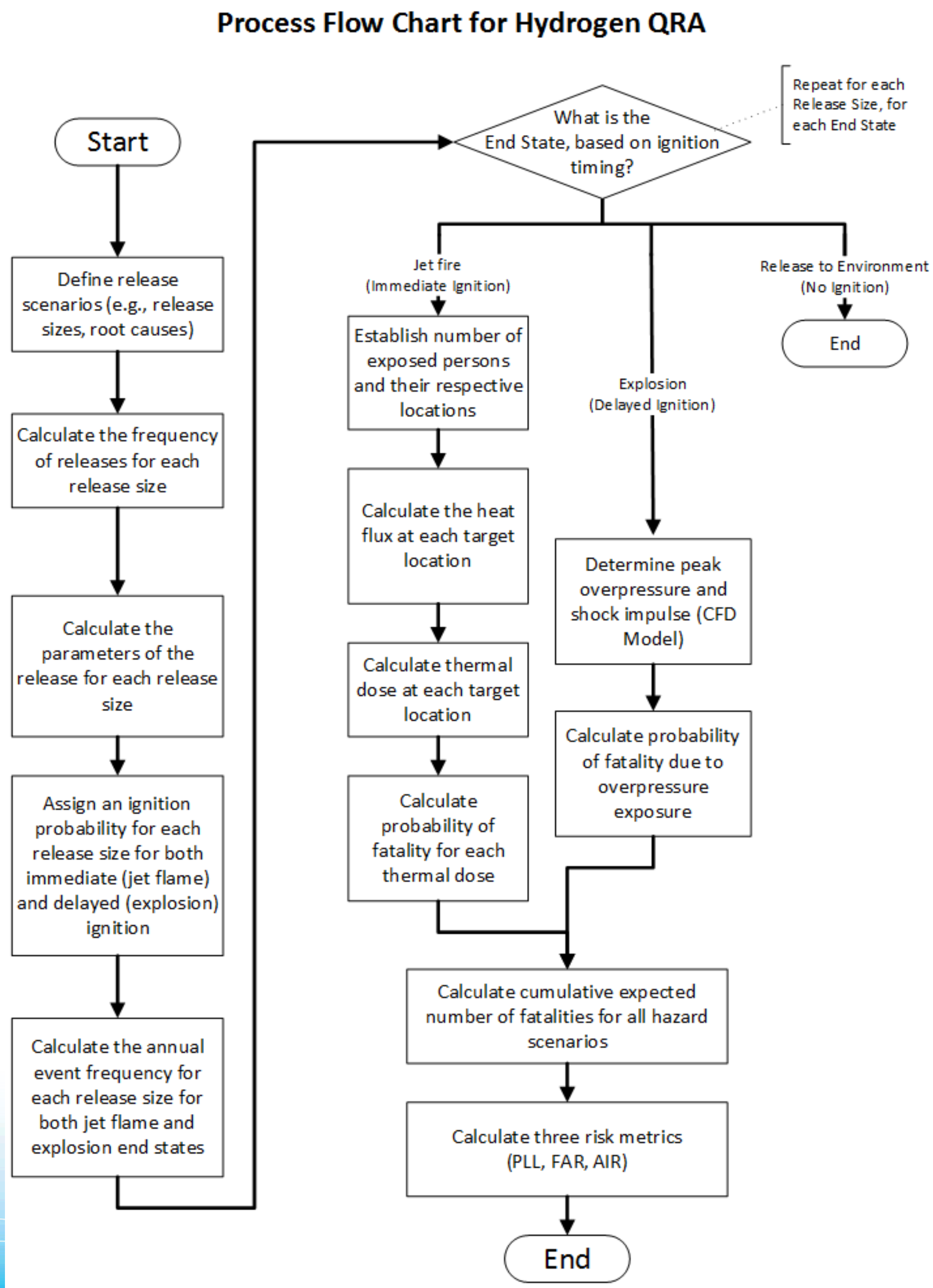
- Properties of jet fires
- Properties of deflagrations (coming soon)

HyRAM: Underlying algorithm (Steps 3 & 4)

Integrates state-of-the-art probabilistic and deterministic models for:

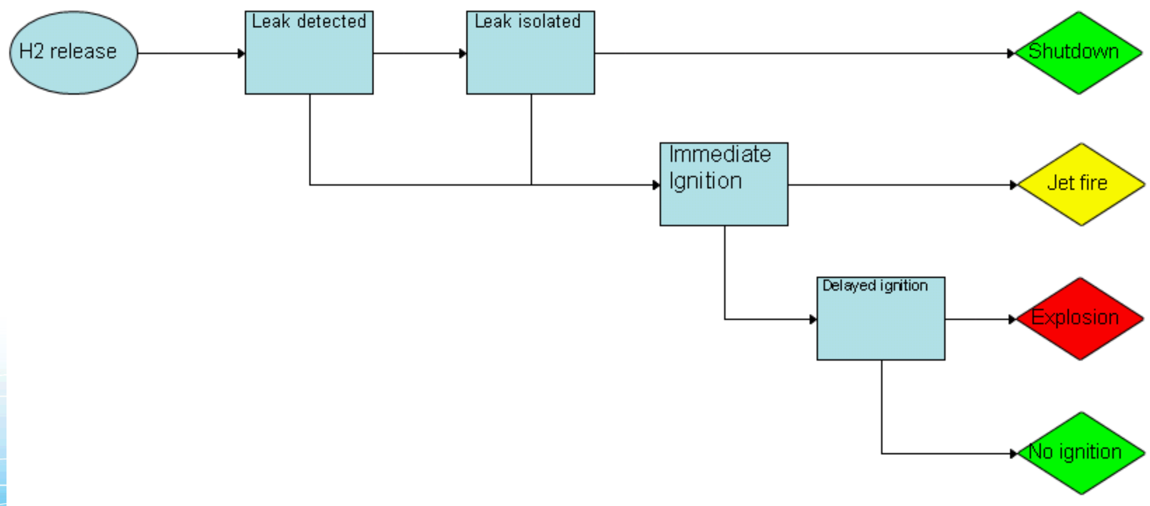
- Component failure
- Ignition occurrence
- Gas release
- Gas dispersion
- Jet flames
- Deflagration / detonation
- Harm to humans

Enables use of best-available models for supporting decisions



Identify Accident Scenarios (1/2)

Purpose	Define scenarios that occur after H2 release
User Inputs	None
Hard-coded elements	- **Hazards considered** Thermal radiation Overpressure (Excluded: debris, asphyxiation) - **Release scenarios** (below)
User options	Include leak detection (yes/no)
Outputs	None



Identify Accident Scenarios (2/2)

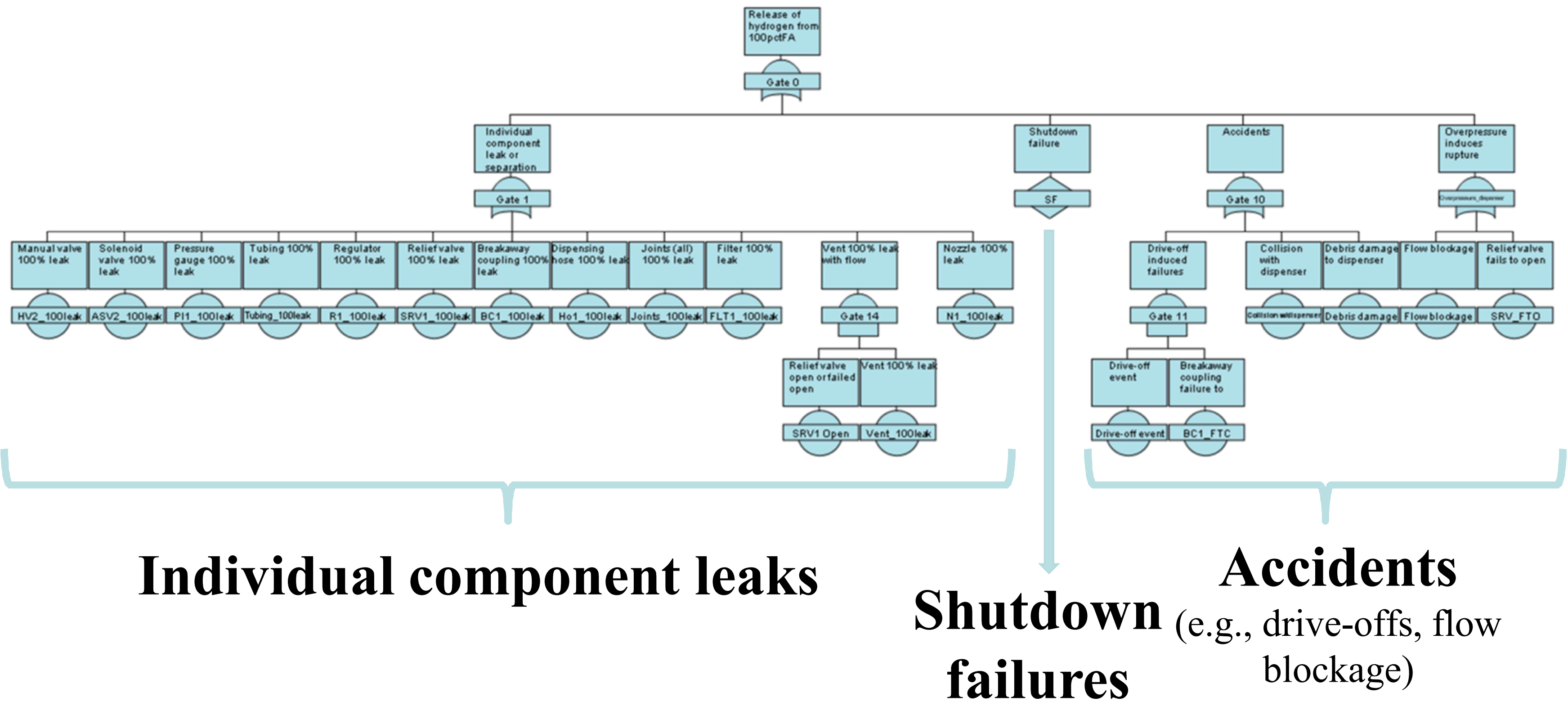
Purpose	Define root causes of H2 releases
User Inputs	- Number of components of 9 types

Hard-coded elements	- Leaks come from 9 types of components:
	  - Compressors
	  - Cylinders
	  - Valves
	  - Instruments
	  - Joints
	  - Hoses
	  - Pipes (m)
	  - Filters
	  - Flanges
	- Accidents & shutdown failures cause 100% releases

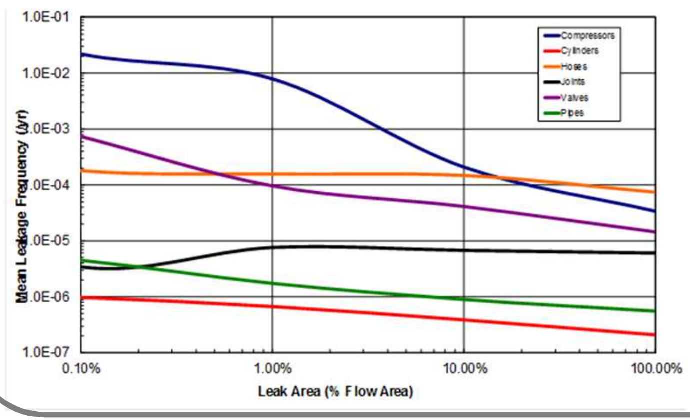
User options	- Option to include (user must write equations)
	  - Accident possibilities
	  - Configuration of shutdown components

Outputs	None

Root causes


Release of hydrogen from 100pctFA
Gate 0
Individual component leak or separation
Gate 1
Shutdown failure
SF
Accidents
Gate 10
Overpressure induces rupture
Manual valve 100% leak
HV2_100leak
Solenoid valve 100% leak
ASV2_100leak
Pressure gauge 100% leak
PI1_100leak
Tubing 100% leak
Tubing_100leak
Regulator 100% leak
R1_100leak
Relief valve 100% leak
SRV1_100leak
Breakaway coupling 100% leak
BC1_100leak
Dispensing hose 100% leak
Ho1_100leak
Joints (all) 100% leak
Joints_100leak
Filter 100% leak
FLT1_100leak
Vent 100% leak with flow
Gate 14
Nozzle 100% leak
N1_100leak
Relief valve open or failed open
SRV1 Open
Vent 100% leak
Vent_100leak
Drive-off induced failures
Gate 11
Drive-off event
Drive-off event
Breakaway coupling failure to
BC1_FTC
Collision with dispenser
Debris damage to dispenser
Debris damage
Flow blockage
Flow blockage
Relief valve fails to open
SRV_FTO
Individual component leaks
Shutdown failures
Accidents
(e.g., drive-offs, flow blockage)

ReleaseFreq

Purpose	Calculate the frequency of releases from system
User Inputs	- Annual number of system demands (Or parameters to calculate)
Hard-coded elements	- Expected annual leak freq. for each component type  Leak freqs. developed from limited H2 data combined w/ data from other industries. LaChance, J et al. *Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards.* SAND2009-0874, **2009**. - Expected probability (per demand) of drive-offs, component failures, accidents, etc. (Generic data) - Equation corresponding to fault tree: $f(H2release) = \sum_{i=9\ comps} n_i * E(f(Leak)_i) + E\big(Pr(accidents)\big) * n_{demands}$
User options	None
Outputs	Matrix of expected annual release frequency (fH2release) for 5 sizes

IgnitionProb

Purpose

Assign ignition probability for each scenario

User Inputs

- In-stream Pressure and Temperature
- Facility Pressure and Temperature
- System pipe diameter

Hard-coded elements

- Probabilities assigned via lookup table*:

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

Based on extrapolation from methane ignition probabilities.

Tchouvelev, A. et al. *Quantitative Risk Comparison of Hydrogen and CNG Refueling Options.* Presentation at IEA Task 19 Meeting. Canadian Hydrogen Safety Program, 2006.

- Uses Nozzle model (ReleaseChars.m) to determine peak hydrogen release rate

User options

None

Outputs

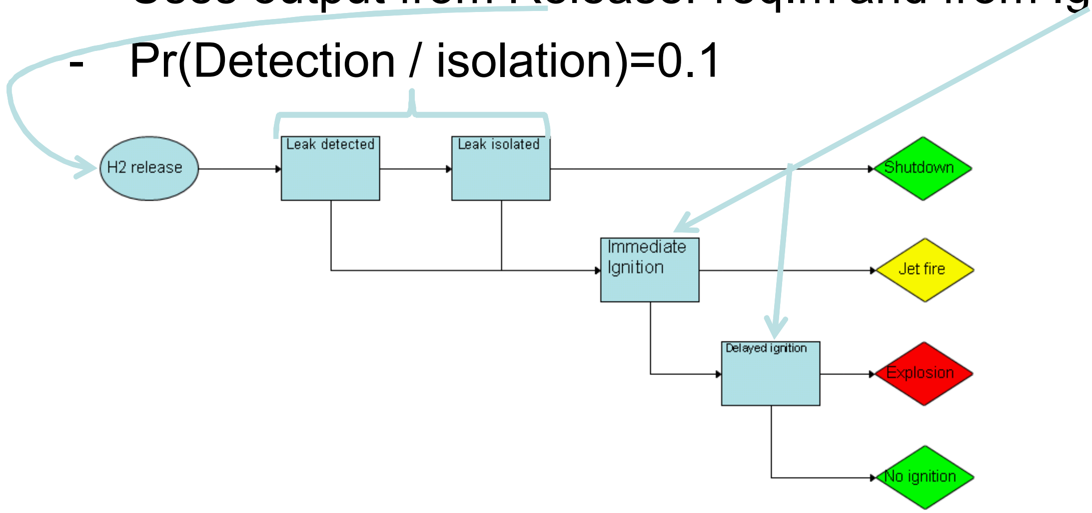
Matrix of ignition probabilities for each release size

*Sandia is currently working on more robust predictive model (“Flame-light up” model)

ScenarioProb

<table>
<tr><td>Purpose</td><td>Calculate the annual frequency of accident scenarios</td></tr>
<tr><td>User Inputs</td><td></td></tr>
<tr><td>Hard-coded elements</td><td>

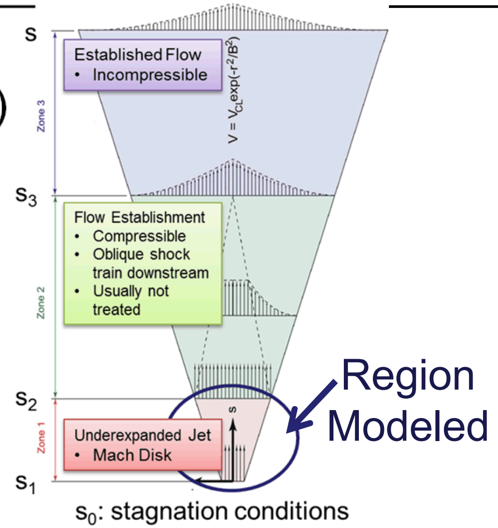
- Implements equations encoded in Event Tree
  - Uses output from ReleaseFreq.m and from IgnitionProb.m
  - Pr(Detection / isolation)=0.1



$f(JetFire)=f(H2Rel)*(1-Pr(Detect))*Pr(Ign_{immed})$

</td></tr>
<tr><td>User options</td><td>None</td></tr>
<tr><td>Outputs</td><td>Matrix of annual frequencies of accident scenarios</td></tr>
</table>

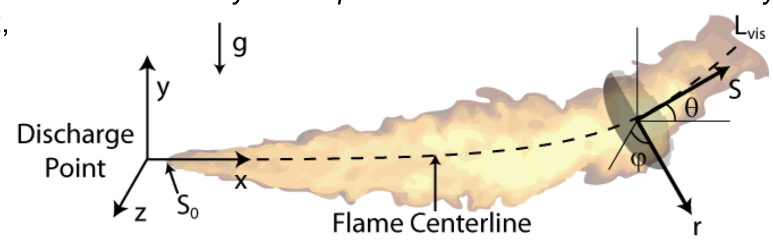
ReleaseChars

Purpose	Calculate characteristics (e.g., gas discharge rate) for the 5 release sizes by implementing a notional nozzle model.
User Inputs	- Pipe diameter - Internal & external pressure and temperature
Hard-coded elements	- Parameters of hydrogen gas and CNG (MW, heat capacity, adiabatic flame temp) - Assumption of choked-flow, non-ideal gas. - Uses Notional Nozzle model based on conservation of mass and momentum, Birch model, and Abel-Noble equation of state. (Ruggles, A. J. & Ekoto, I. W. *Ignitability and mixing of underexpanded hydrogen jets*. International Journal of Hydrogen Energy, 2012, 37, 17549-17560 .) 
User options	None
Outputs	- **Gas jet exit conditions**: Mass flow rate (kg/s), Effective temperature, density, velocity, Mach number, release area of

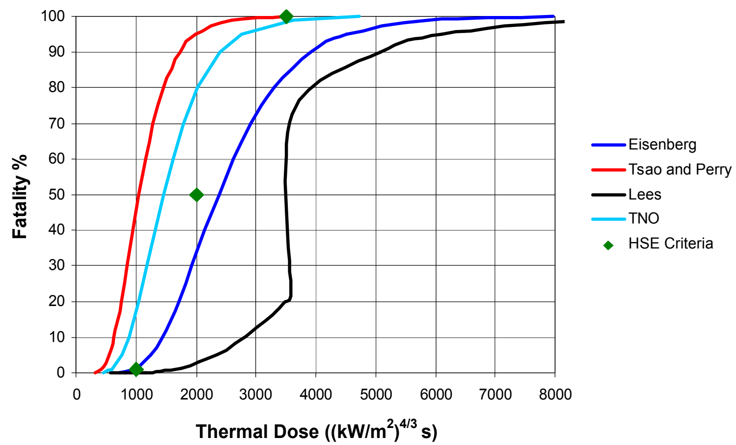
Knowledge of jet exit conditions is used to assign ignition probabilities and to predict consequences

Scenarios → Likelihood → Consequences

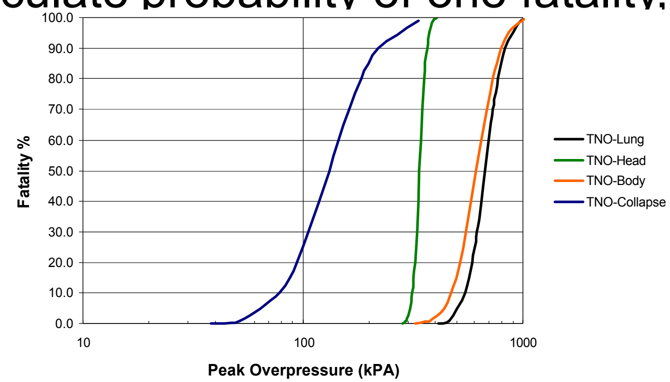
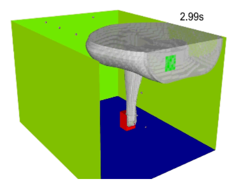
FlameRadiation

Purpose	Calculates the radiant fraction, flame residence time, visible flame length, and heat flux for a hydrogen flame, at a given position
Inputs	- Jet properties predicted from ReleaseChars.m - Axial and radial location where to be predicted (Currently, positions are generated for 50 workers, by sampling a normal distribution)
Hard-coded elements	- Parameters of hydrogen (MW, Atomic structure, adiabatic flame temp, heat of combustion). - Calculation based on multi-source models (Houf, W. & Schefer, R. *Predicting radiative heat fluxes and flammability envelopes from unintended releases of hydrogen*. Intl Jour of Hydrogen Energy, 2007, 32, 
User options	Can change number of workers and form of distribution used to generate worker positions
Outputs	Heat flux at a given position

ThermalFatality

Purpose	Calculates the probability of fatality given a thermal exposure
Inputs	- Heat flux, I (from FlameRadiation.m) - Thermal exposure time, t (user generated, currently 60s)
Hard-coded elements	- Thermal Dose: $V = I^{4/3}t$ - Probit functions calculate probability of one fatality, given thermal dose: 
User options	Choice of thermal probit functions: Eisbenberg, Tsao, TNO, Lees (Selection criteria are discussed in LaChance, J.; Tchouvelev, A. & Engebo, A. Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure International Journal of Hydrogen Energy, 2011, 36, 2381-2388)
Outputs	Probability of fatality from thermal exposure for each worker, summed over all workers.

OverpressureFatality

Purpose	Calculates the probability of a single fatality, given exposure to pressure waves
Inputs	- Peak overpressure, P_s (Currently a user input) * - Impulse (Currently a user input)*
Hard-coded elements	- Probit functions calculate probability of one fatality, given peak pressure :  
User options	Choice of pressure probit functions: Eisenberg (Lung), HSE (Lung) Tsao, TNO (Head impact, structural collapse, or debris). (Selection criteria are discussed in LaChance, J.; Tchouvelev, A. & Engebo, A. Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure International Journal of Hydrogen Energy, 2011, 36, 2381-2388)
Outputs	Probability of fatality from pressure exposure for each worker, summed over all workers.

*Sandia is currently working on first-order predictive model for deflagrations

Risk calculation: PLLetc

Purpose	Calculate the risk in terms of FAR, PLL, and AIR
Hard-coded elements	• Potential Loss of Life (PLL) $$PLL = \sum_n \sum_j (f_{nj} \cdot c_{nj})$$ – (Frequency of each scenario from ScenarioFreq.m multiplied by consequences from both Fatality.m files, summed over all possible scenarios) • Fatal Accident Rate (FAR) $$FAR = \frac{PLL \cdot 10^8}{Exposed\ hours} = \frac{PLL \cdot 10^8}{N_{staff} \cdot 8760}$$ • Where N_{staff} = number of workers – AIR=FAR*10^-8*Hrs
Outputs	Three risk metrics: PLL, FAR, AIR

Summary

- HyRAM toolkit built to facilitate H2 industry access to QRA & behavior models to enable industry-lead QRA activities, safety analyses, etc.
  - Evaluate and revise C&S requirements
  - Identify design changes to enhance safety (and understand which design changes have little safety impact)
- Ongoing work to add overpressure calculation module; add sensitivity analysis capabilities; add user interfaces; to develop baseline risk metrics for a generic prescriptive-compliant system; link modules to NFPA2 Ch. 5 Performance Scenarios to facilitate alternative compliance option or performance-based compliance option (NFPA2 mode)
- Opportunity for HSP feedback on early interfaces

Thank you!

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Risk & Reliability Analysis at Sandia National Laboratories

Next demonstration: DOE AMR Side meeting: Thursday June 19th, 4:30-6pm., Marriott Wardman Park Hotel (Room TBD)

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Backup

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QRA– What does success look like?

- **Repeatability** – Different teams should be able to produce the same result
  - Requires: Defined objectives and scope
  - Requires: Clear definitions of failure modes, consequences, the system, and criteria (or data used) to assign severity and likelihood
- **Traceability** – Final analysis must reflect actual product
  - Document the system being analyzed, and make sure it matches the system as built and operated
- **Comparable** - Differences in QRA results should be due to differences in designs, not due to models.
  - Necessitates standardized set of models and data
- **Verifiable** – Data, models, system, and analysis are sufficiently documented for a peer reviewer to evaluate correctness
- **Complete** – Encompasses all hazards