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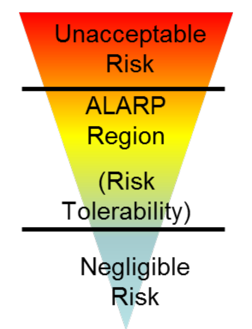

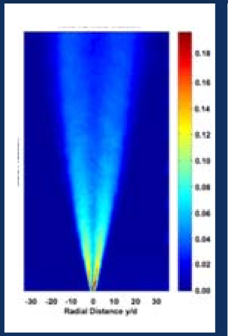

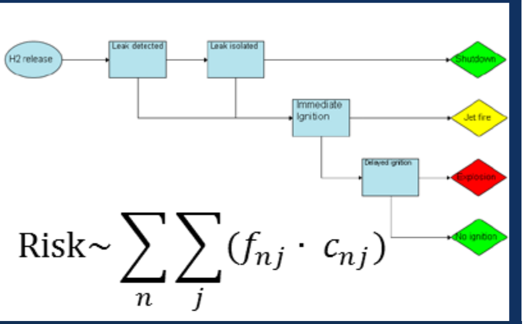

$$\text{Risk} \sim \sum_n \sum_j (f_{nj} \cdot c_{nj})$$

Sandia QRA toolkit – Version 0

Katrina M. Groth, Ph.D.

Sandia National Laboratories

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Yesterday we discussed

- History of risk-informed approach for H2 C&S
- How QRA has been used in H2 C&S and other applications
- Where else QRA can be used for H2 or CNG applications

Objective of this presentation

- Tell you what the current tool does (and doesn’t) do.
- Prepare you for breakout sessions to identify priorities/next steps for the tool.

Risk Assessment

- **Generic term!**
    - Encompasses a range of techniques, conducted for a range of purposes, in a range of industries.
- NFPA provides guidance to for risk assessment for C&S:
    - Rose (2007) *Guidance Document for Incorporating Risk Concepts into NFPA Codes and Standards*
    - Does not require a particular analysis method, analysis goal, criteria, etc.
    - Lack of application-specific tools

What is Risk Assessment?

Risk Analysis

- A process used to identify and characterize risk in a system
  - What could go wrong?
  - How likely is it?
  - What are the consequences?

+

Risk Management

- Provide inputs to decision makers on:
  - Sources of risk
  - Strategies to reduce risk.

Can be qualitative or quantitative

Quantitative form referred to as QRA

Risk quantification

- **Risk**: A measure of the potential detrimental outcomes of an activity subject to hazard.
    - **Scenarios**: What can go wrong?
    - **Likelihoods:** How likely is it?
    - **Consequences:** What are the consequences (losses)?

$$Risk \propto \sum_{scenarios} (likelihood \cdot consequences)$$

Risk analysis > Math

- The purpose of risk analysis is to support decision-making, not to produce numbers.
  - Risk analysis provides decision support, not hard recommendations or objective values.
  - QRA is a process to build consensus, to encourage discourse among interested parties, to explore priorities, to build a common basis for safety discussions

We cannot replace difficult ethical and political deliberations with a mathematical one-dimensional formula

(Terje Aven, *Foundations of Risk Analysis, 2003*)

Outline

- What you need to do before using the toolkit
- Toolkit overview
- Modules of the toolkit

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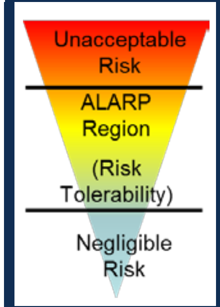
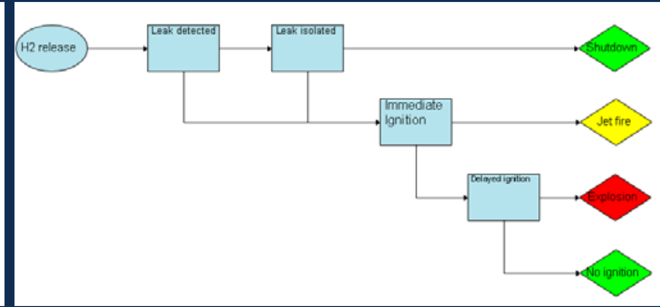
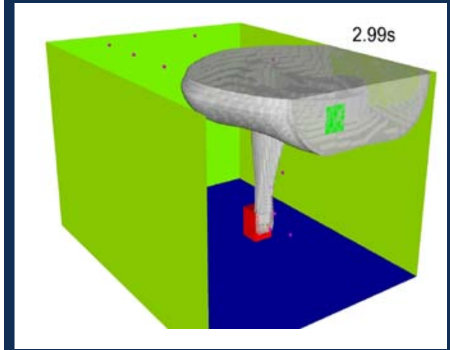
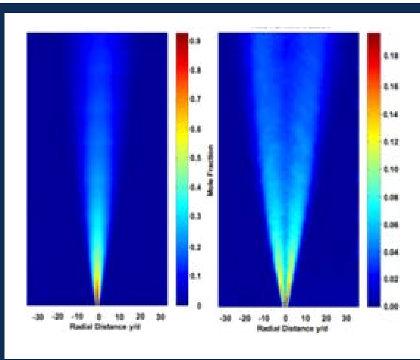
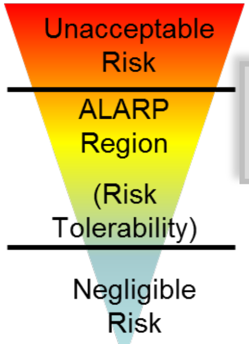








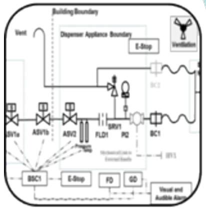
QRA Process Overview

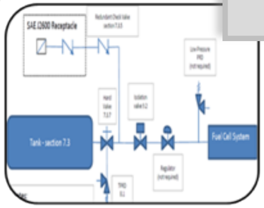


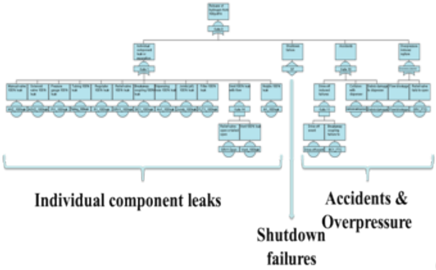
1. Set analysis goals

QRA Process

2. System & hazard description


Dispenser

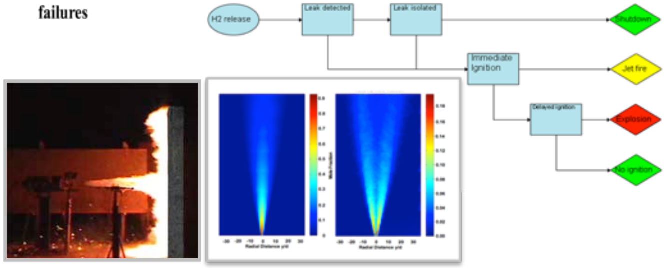

Fuel Cell



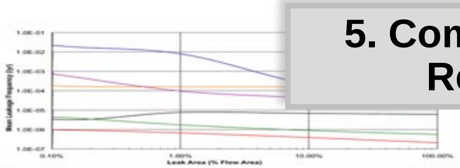
3. Cause analysis

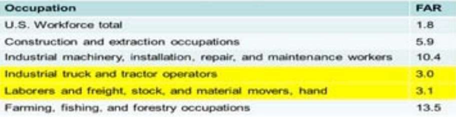
Focus of Toolkit

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

Analysis goals

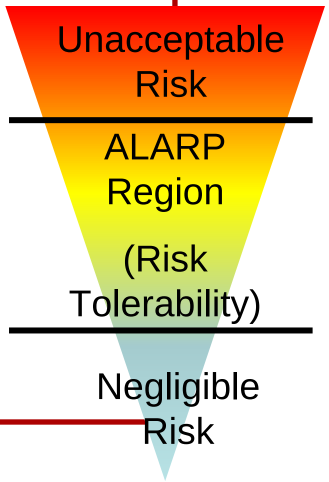
- What type of risk assessment are you doing?
- What is the end goal?

Risk of What?

- Human fatalities
  - Individual or group?
  - Workers? Public? Adults? Children?
- Injuries
- Economic losses
- Environmental damage
- System damage
- Cultural loss
- Etc.

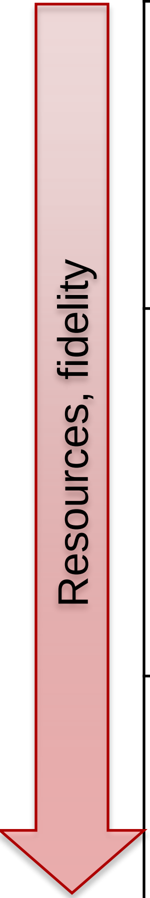
In terms of what?

- Number
  - Expectation or distribution?
- Rate
- Value
- Etc.

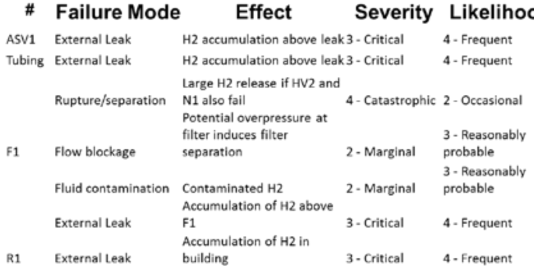
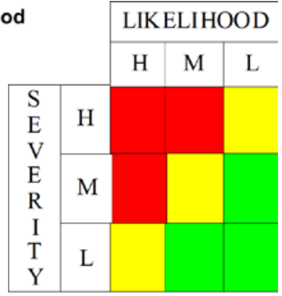
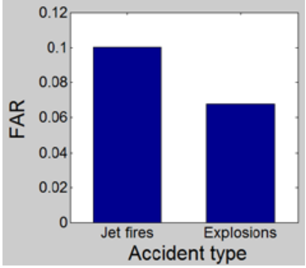
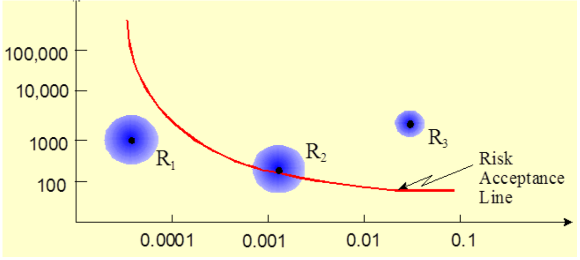
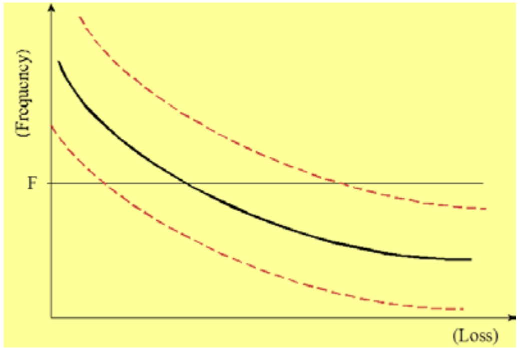


NFPA suggests a range of metrics for each of these risks in Rose (2007).

Risk Assessment methods



Resources, fidelity

Type	Example methods	Example outputs
Qualitative to semi-quantitative	- FMEA - HAZOP - PHA	 
Quantitative	**QRA [Quantitative Risk Assessment]** - Fault Trees - Event Trees - Bayesian Networks	Above, plus:  
Quantitative with uncertainty propagation		Above, plus: $R_i \sim \text{Loss} * \text{Probability} + \varepsilon$ 

#	Failure Mode	Effect	Severity	Likelihood
ASV1	External Leak	H2 accumulation above leak	3 - Critical	4 - Frequent
Tubing	External Leak	H2 accumulation above leak	3 - Critical	4 - Frequent
	Rupture/separation	Large H2 release if HV2 and N1 also fail	4 - Catastrophic	2 - Occasional
F1	Flow blockage	Potential overpressure at filter induces filter separation	2 - Marginal	3 - Reasonably probable
	Fluid contamination	Contaminated H2	2 - Marginal	3 - Reasonably probable
	External Leak	Accumulation of H2 above F1	3 - Critical	4 - Frequent
R1	External Leak	Accumulation of H2 in building	3 - Critical	4 - Frequent

		LIKELIHOOD		
		H	M	L
SEVERITY	H	🟥	🟥	🟨
	M	🟥	🟨	🟩
	L	🟨	🟩	🟩

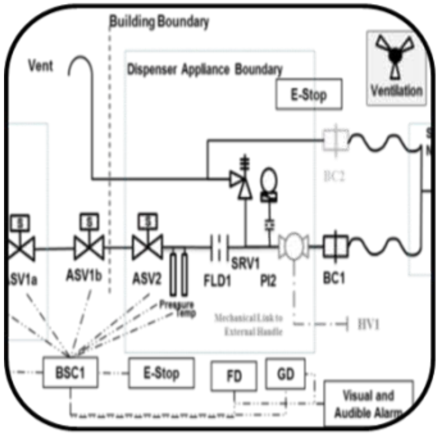
$R_i \sim \text{Loss} * \text{Probability}$

System Description

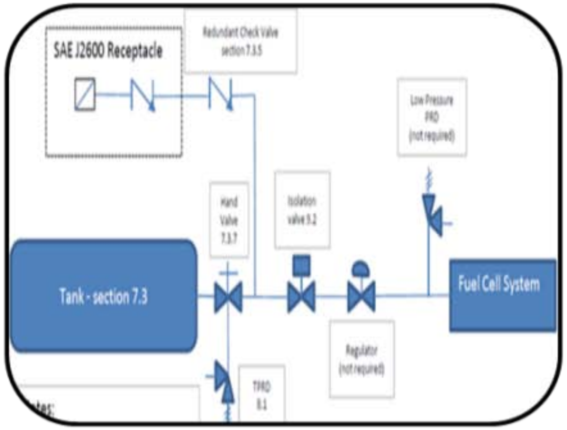
- What do you mean by "system"? What are the major subsystems to include? How do they interface? What level of detail will be addressed?

- What are the relevant parameters of these subsystems?

Example: System description



Dispenser

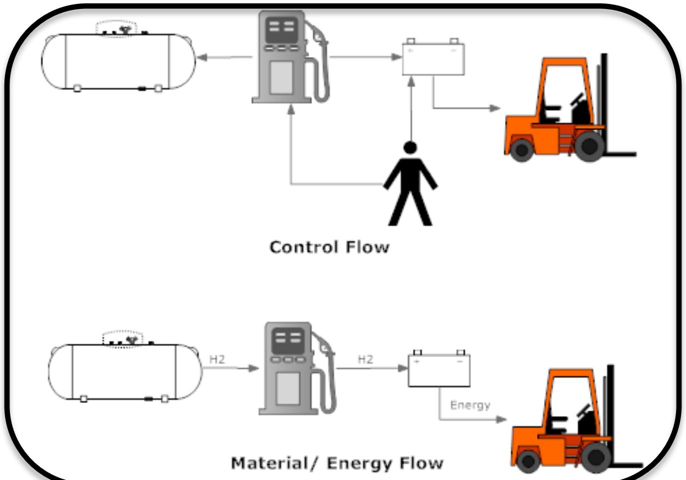


Fuel Cell

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

- 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.	• Explosion? Impacts? • Fire? Freezing? • Corrosion? Oxidation? • …

Example: Hazards of GH2 dispensing

Associated with H2 gas releases:

- Heat radiation & direct flame contact (jet fires)
- Overpressures (deflagrations and explosions)
  - Direct
  - Indirect
- Debris damage

Effects on targets:

- Potentially fatal injuries to workers
- Damage to buildings and assets

Outline

- What you need to do before using the toolkit
- **Toolkit overview**
- Modules of the toolkit

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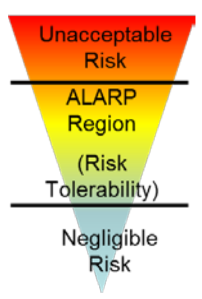

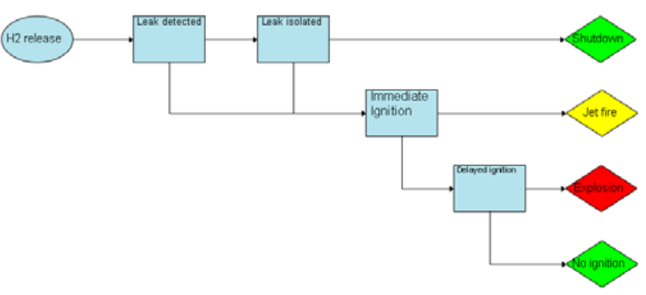

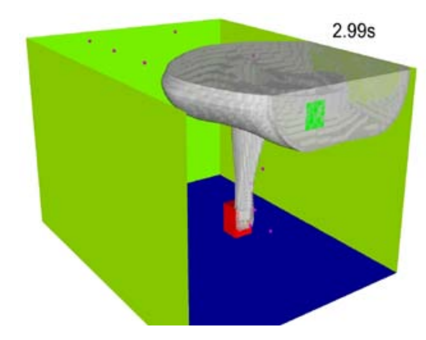

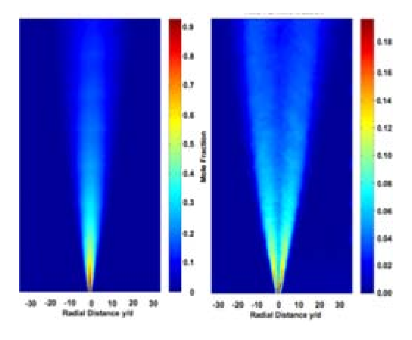

Background

- Version 0 was built to help establish risk of hydrogen vehicle indoor fueling operations, to inform NFPA 2 *Hydrogen Technologies Code*, chapter 10: Indoor fueling
    - Risk to be expressed as the Fatal Accident Rate (FAR).
- Unfortunately, no tool exists for conducting such analysis

Background

- Previous work (without toolkit)
  - Established data for frequency of H2 releases, based on data from related industries and some H2 data
    - More data --> More robust analysis
  - Documented variety of human harm models (FY10)
  - Developed first order model for predicting heat flux from jet flames (FY08)
- Toolkit integrates this previous work into a single computer code

Initial needs

- Need to calculate multiple risk metrics
- Probability side
  - Need to incorporate hydrogen-specific data (including ability to update)
  - Ability to functionally specify how data is used
- Need first-order models for calculating multiple sequential consequences
  - Gas release behavior
  - Gas dispersion and accumulation behavior
  - Jet fires, explosions
  - Impact of flames and overpressure on humans, structures, etc.

User profile

- Familiarity with QRA
  - Knowledge of QRA assumptions, limitations, interpretation
  - Ability to program Fault Trees (FTs) without graphical interface
  - Ability to post-process results for the decision-maker
- Ability to use Matlab
- 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.

Outline

- What you need to do before using the toolkit
- Toolkit overview
- **Modules of the toolkit**

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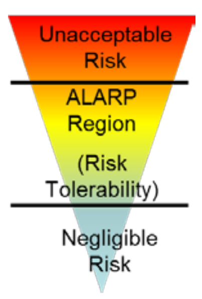
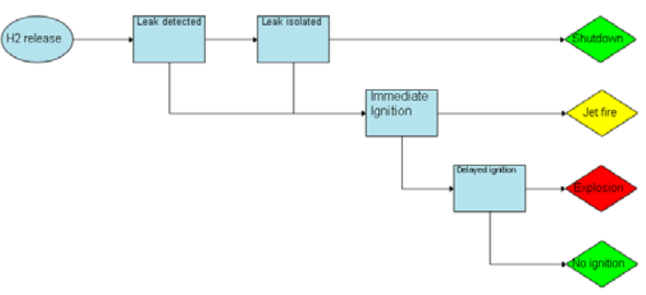
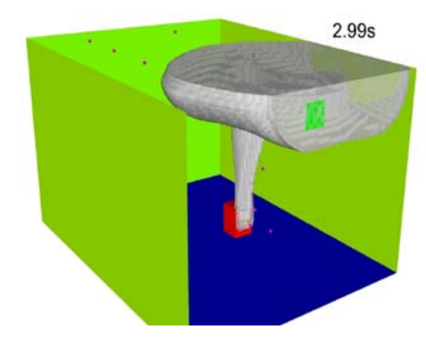
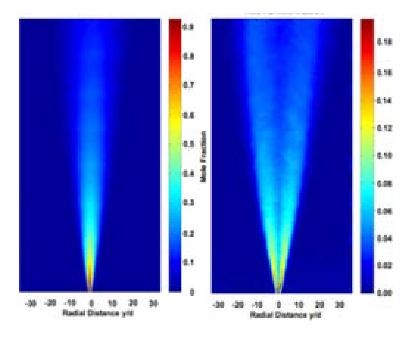








Risk metrics [currently] supported

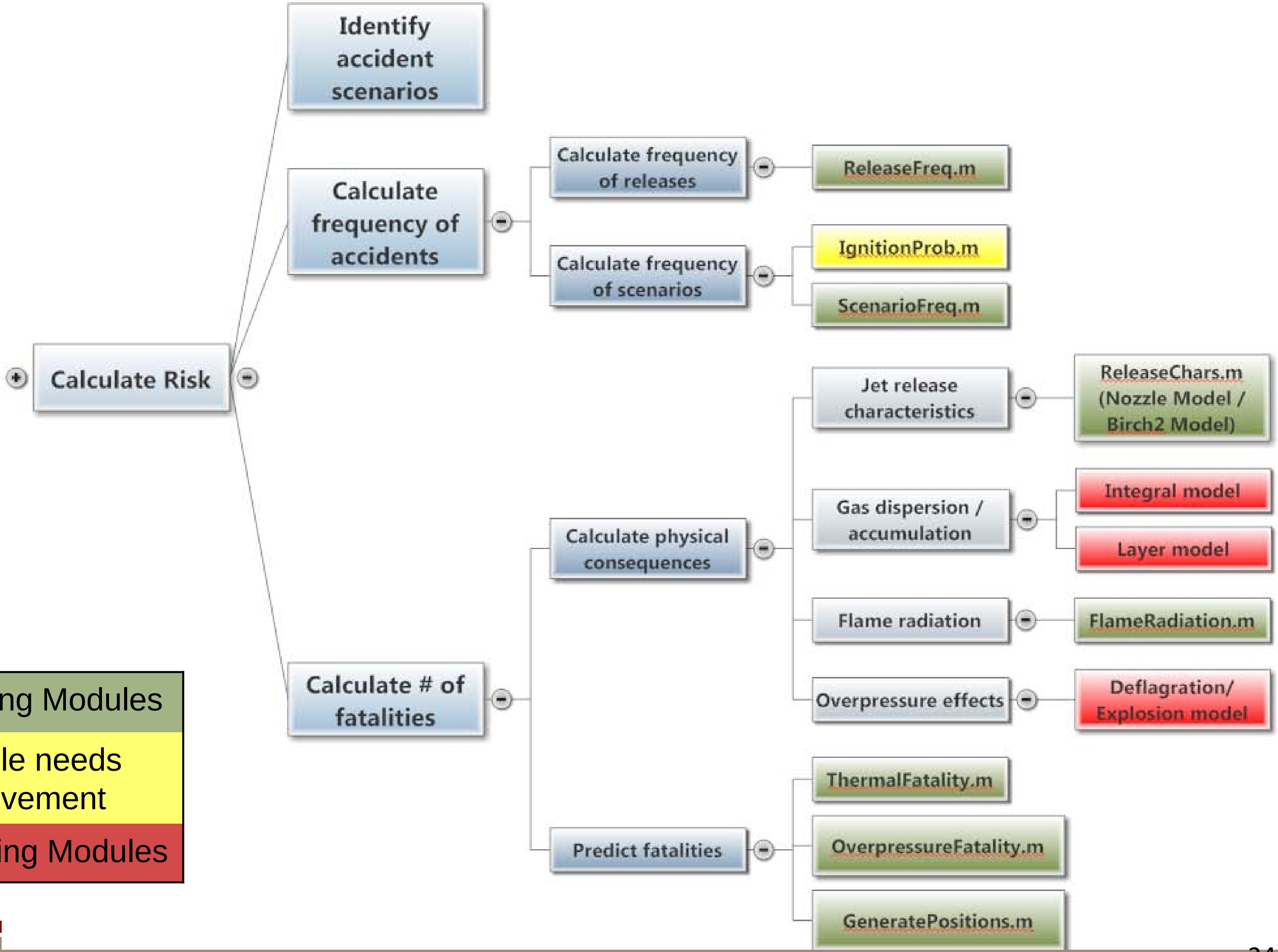
Code designed to output 3 risk metrics:

- **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:

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

Modules in QRA tool



- Calculate Risk
  - Identify accident scenarios
  - Calculate frequency of accidents
    - Calculate frequency of releases
      - ReleaseFreq.m
    - Calculate frequency of scenarios
      - IgnitionProb.m
      - ScenarioFreq.m
  - Calculate # of fatalities
    - Calculate physical consequences
      - Jet release characteristics
        - ReleaseChars.m (Nozzle Model / Birch2 Model)
      - Gas dispersion / accumulation
        - Integral model
        - Layer model
      - Flame radiation
        - FlameRadiation.m
      - Overpressure effects
        - Deflagration/ Explosion model
    - Predict fatalities
      - ThermalFatality.m
      - OverpressureFatality.m
      - GeneratePositions.m

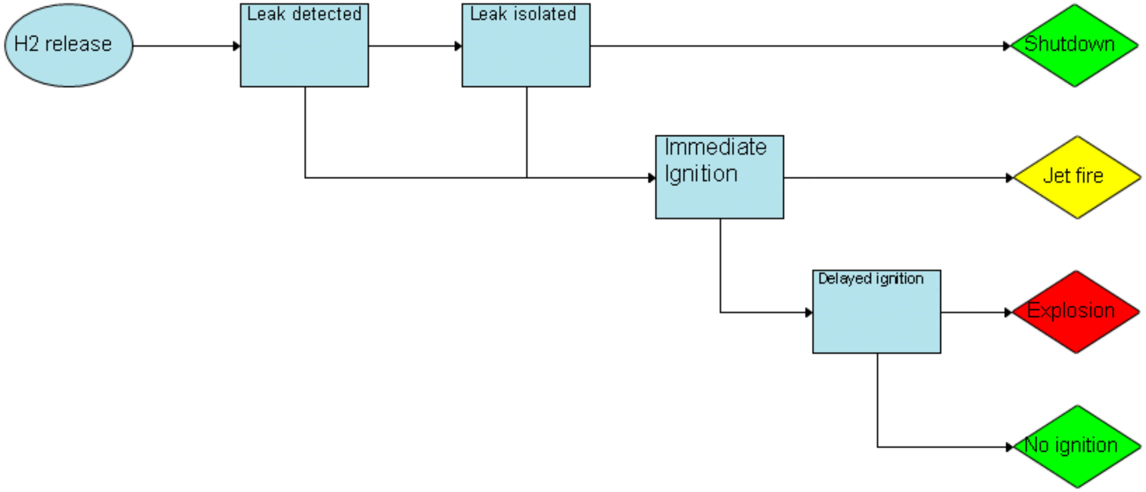
Existing Modules

Module needs improvement

Pending Modules

Identify Accident Scenarios (1/2)

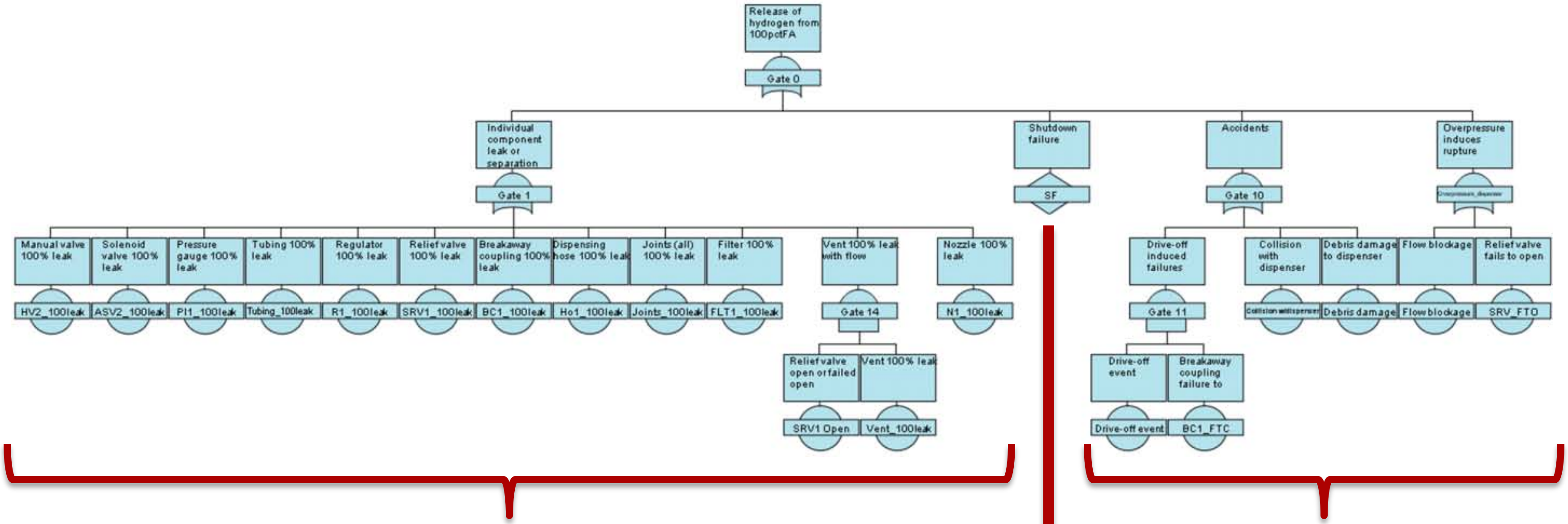
Purpose	Define scenarios that occur after H2 release
User Inputs	None
Hard-coded elements	- **Hazards considered** Thermal radiation Overpressure (Excluded: debris, asphyxiation) - **Release scenarios** (below)
User options	Include leak detection (yes/no)
Outputs	None



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



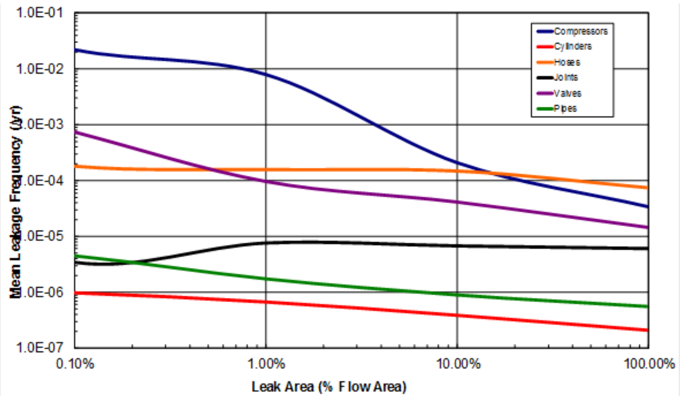
Individual component leaks

Shutdown failures

Accidents

(e.g., drive-offs, flow blockage)

ReleaseFreq.m

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: $f(H2release) = \sum_{i=9\ comps} n_i * E(f(Leak)_i) + E\left(Pr(accidents)\right) * n_{demands}$
User options	None
Outputs	Matrix of expected annual release frequency (fH2release) for 5 sizes

IgnitionProb.m

Purpose

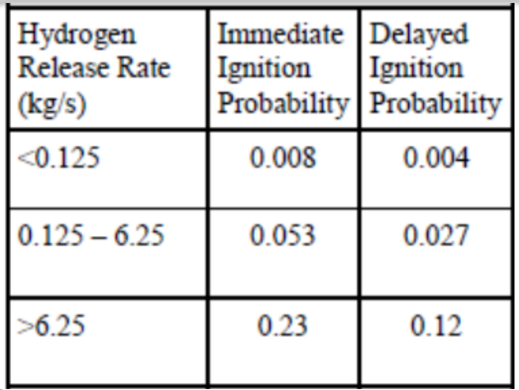
Assign ignition probability for each scenario

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

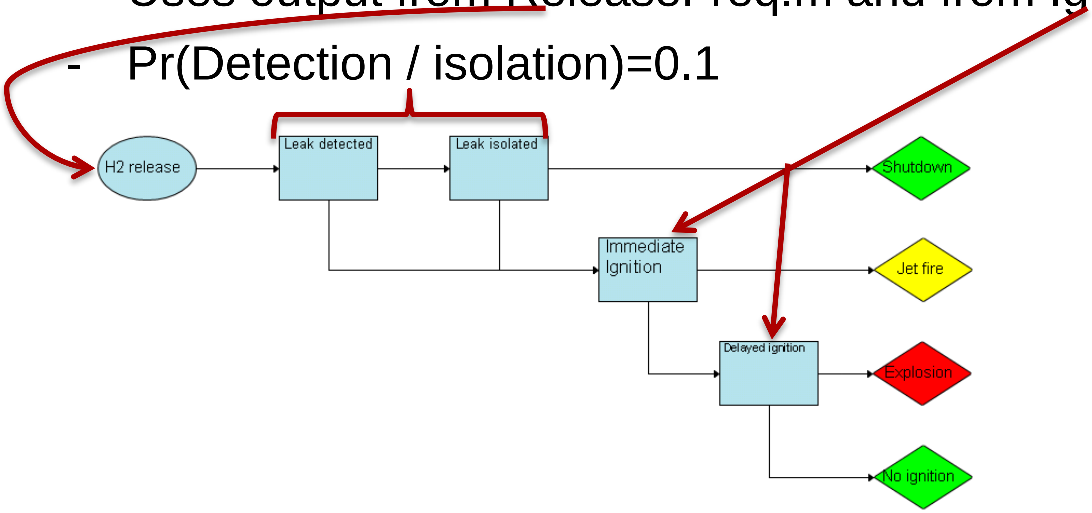
None

Outputs

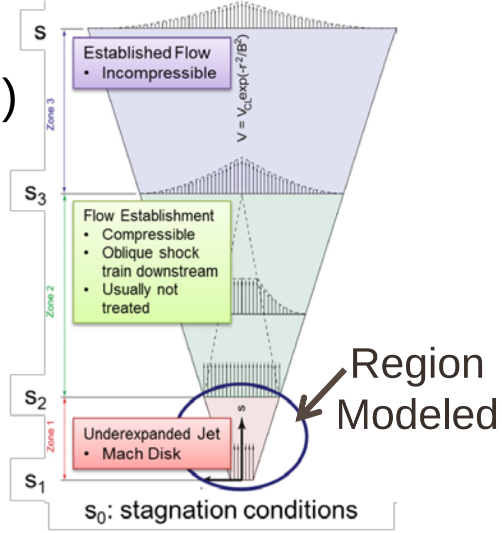
Matrix of ignition probabilities for each release size

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

ScenarioFreq.m

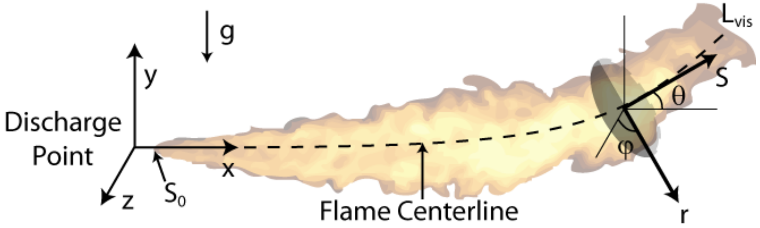
Purpose	Calculate the annual frequency of accident scenarios
User Inputs	
Hard-coded elements	- Implements equations encoded in Event Tree - Uses output from ReleaseFreq.m and from IgnitionProb.m - Pr(Detection / isolation)=0.1  $f(JetFire)=f(H2Rel)*(1-Pr(Detect))*Pr(Ign_{immed})$
User options	None
Outputs	Matrix of annual frequencies of accident scenarios

ReleaseChars.m

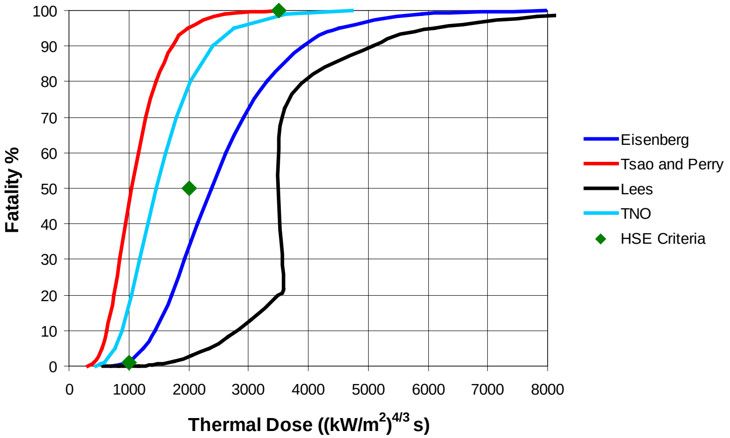
Purpose	Calculate characteristics (e.g., gas discharge rate) for the 5 release sizes by implementing a notional nozzle model.
User Inputs	- Pipe diameter - Internal & external pressure and temperature
Hard-coded elements	- Parameters of hydrogen gas and CNG (MW, heat capacity, adiabatic flame temp) - 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

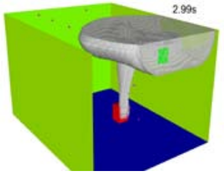
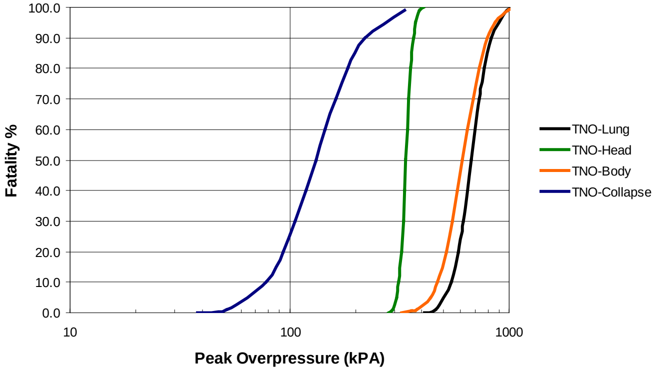
FlameRadiation.m

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, 136-151.) 
User options	Can change number of workers and form of distribution used to generate worker positions
Outputs	Heat flux at a given position

ThermalFatality.m

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.m

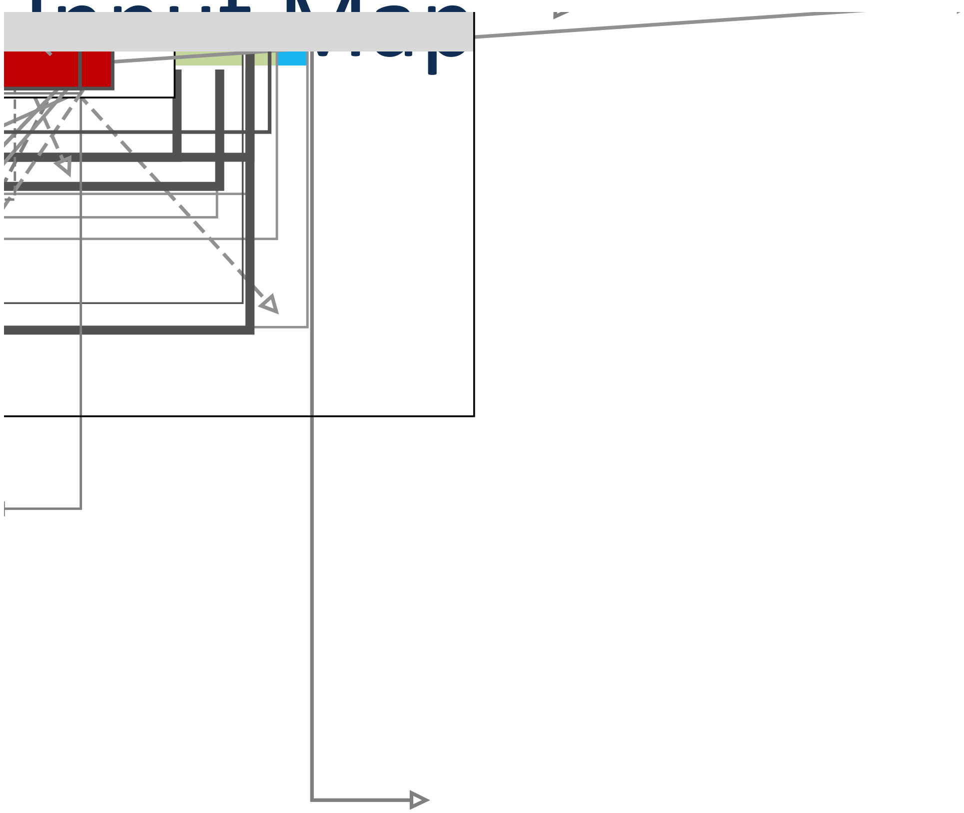
Purpose	Calculates the probability of a single fatality, given exposure to pressure waves
Inputs	- Peak overpressure, P_s (Currently a user input) * - Impulse (Currently a user input)* 
Hard-coded elements	- Probit functions calculate probability of one fatality, given peak pressure : 
User options	Choice of pressure probit functions: Eisbenberg (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

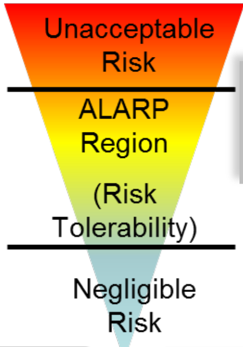
Risk calculation: PLLetc.m

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)
Outputs	Three risk metrics: PLL, FAR, AIR

Input Map



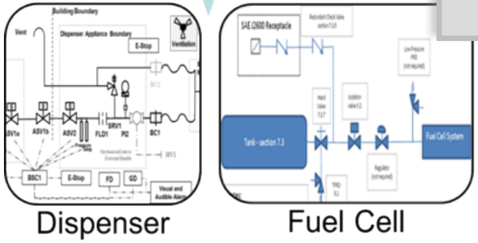
After using the toolkit….



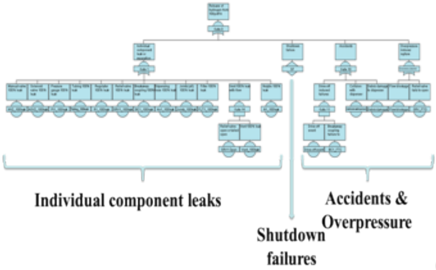
1. Set analysis goals

QRA Process

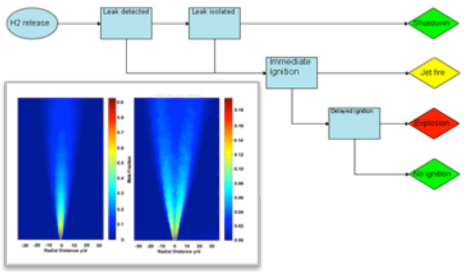
2. System & hazard description



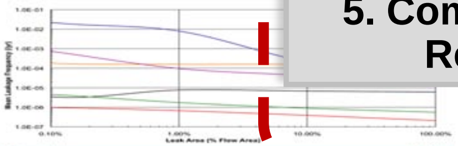
3. Cause analysis



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

Summary

- This presentation discussed the modules of QRA toolkit V0
- Next: Discuss directions for Version 1 of the toolkit
  - How do you intend to use QRA? (Or, if you're not a user: how would C&S developers want to use QRA)
  - What level of detail will help users make an informed decision?
  - Which risk metrics to include?
  - What kind of graphical output?
  - What modifications are necessary for other gases?

Thank you!

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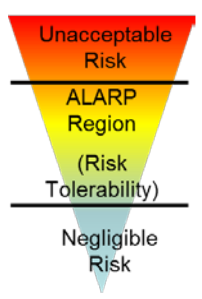
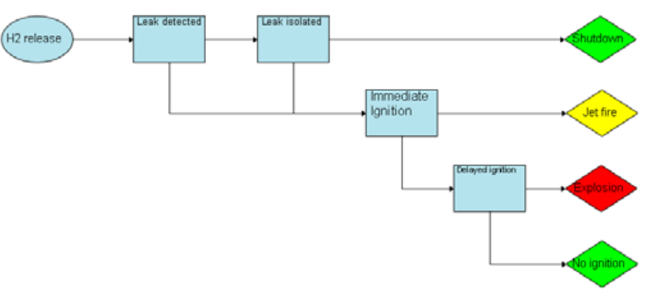
kgroth@sandia.gov

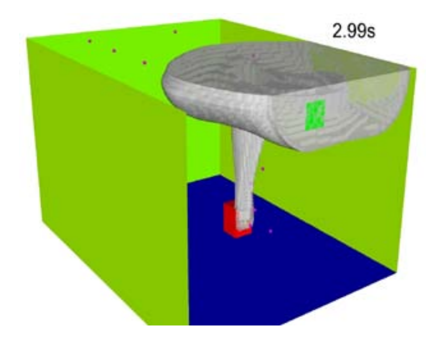
Risk & Reliability Analysis at Sandia National Laboratories

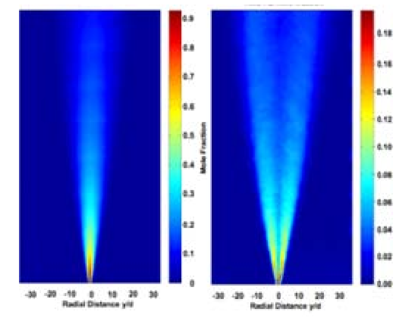
Exceptional service in the national interest

Sandia National Laboratories









BACKUP SLIDES

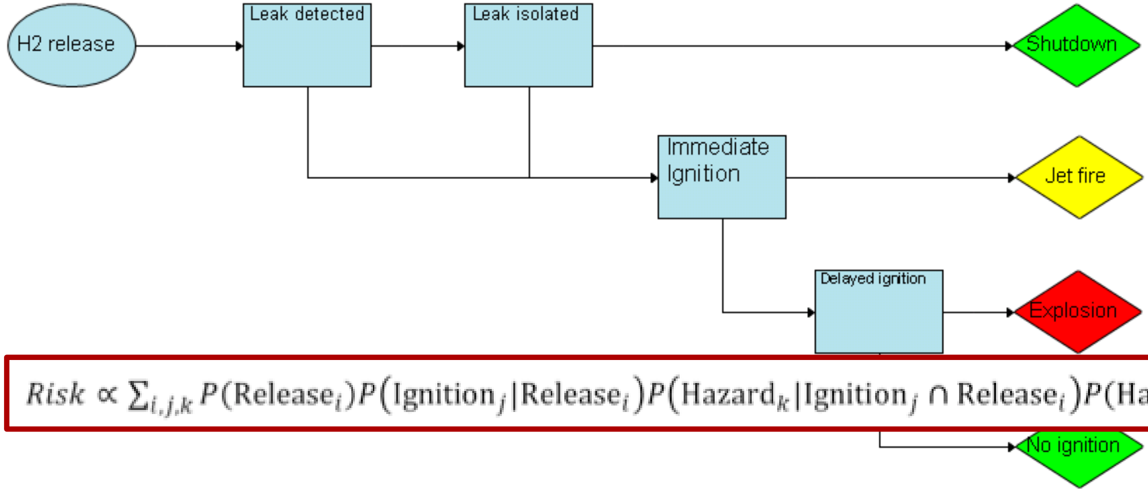
.m

Purpose	
User Inputs	
Hard-coded elements	
User options	
Outputs	

Copy this slide and use to describe code for each of the modules.

Calculate Frequency of Accidents

Purpose	Calculate the annual frequency of accident scenarios
Modules	- ReleaseFreq.m - IgnitionProb.m - ScenarioFreq.m
Interfaces with	- Scenarios, root causes, and user inputs from “Identify Accident Scenarios”



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

Required user input

System description:

System design

- Components
  - Compressors (#)
  - Cylinders (#)
  - Valves (#)
  - Instruments (#)
  - Joints (#)
  - Hoses (#)
  - Pipes (m)
  - Filters (#)
  - Flanges (#)
- Configuration of Shutdown components [Must hard code]

System parameters

- Pipe outer diameter & wall thickness
- Internal temperature, pressure
- External temperature, pressure
- Amount of hydrogen
- Number of demands (annual)

Facility parameters

- Dimensions
- Population: number of persons, locations, exposed (working) hours

Exposure parameters:

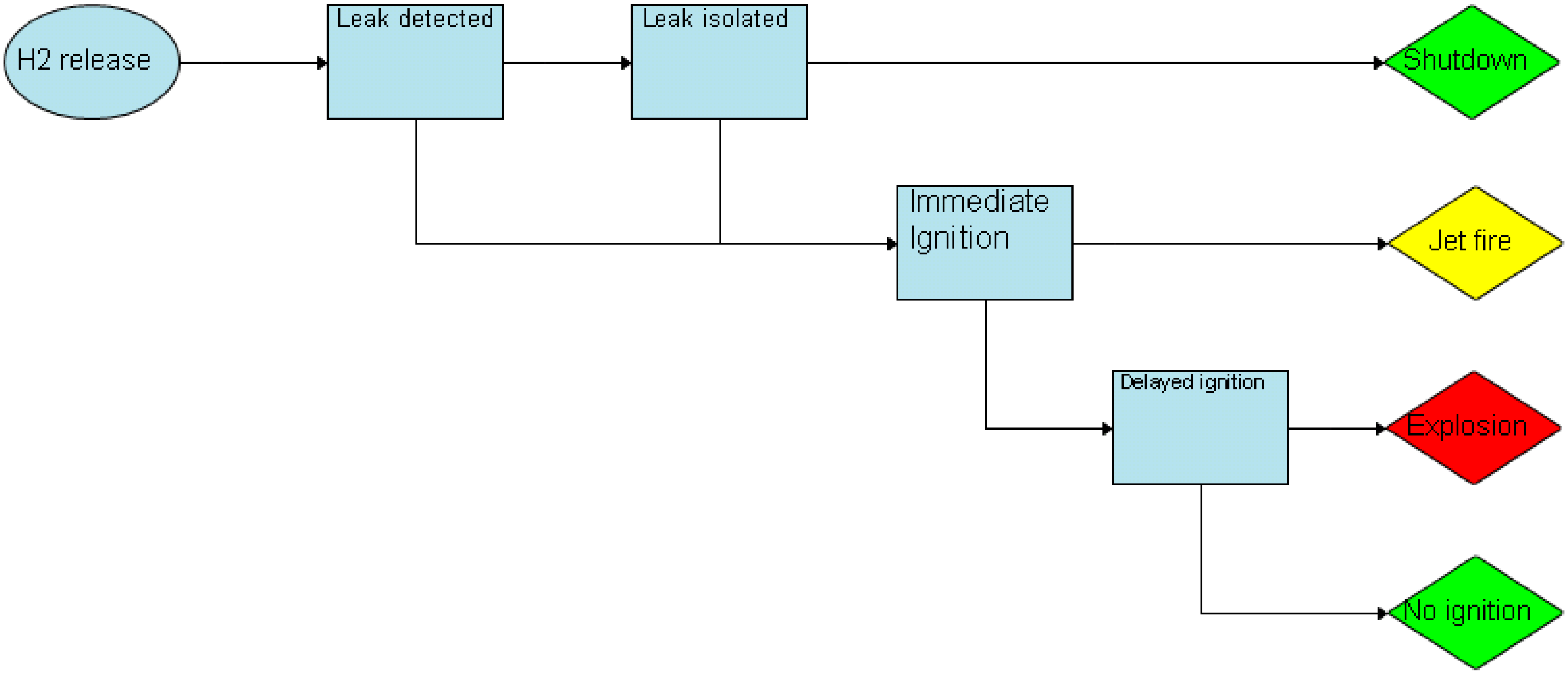
- Flame exposure time
- Choice of probit function for thermal, overpressure effects
- Expected peak overpressure and impulse (currently from CFD)

Hard-coded data

Data:

- Component release frequencies (per dispenser-year)
- Component failure frequencies (per demand)
- Accident frequencies (per dispenser-year)
- Ignition probability
- Gas detection probability

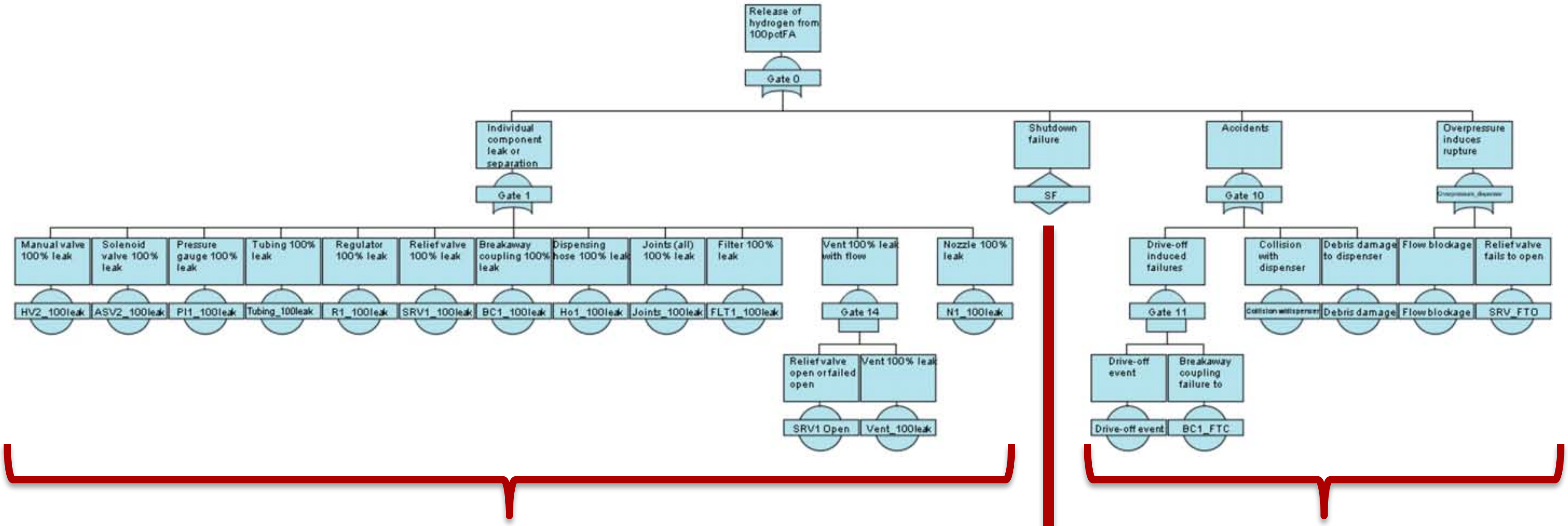
Cause analysis: Release scenarios



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

Quantified with H2 data (if available), generic data, existing probability models – ongoing efforts are working to improve the quantitative model.

Cause analysis: Release causes



Individual component leaks

Shutdown failures

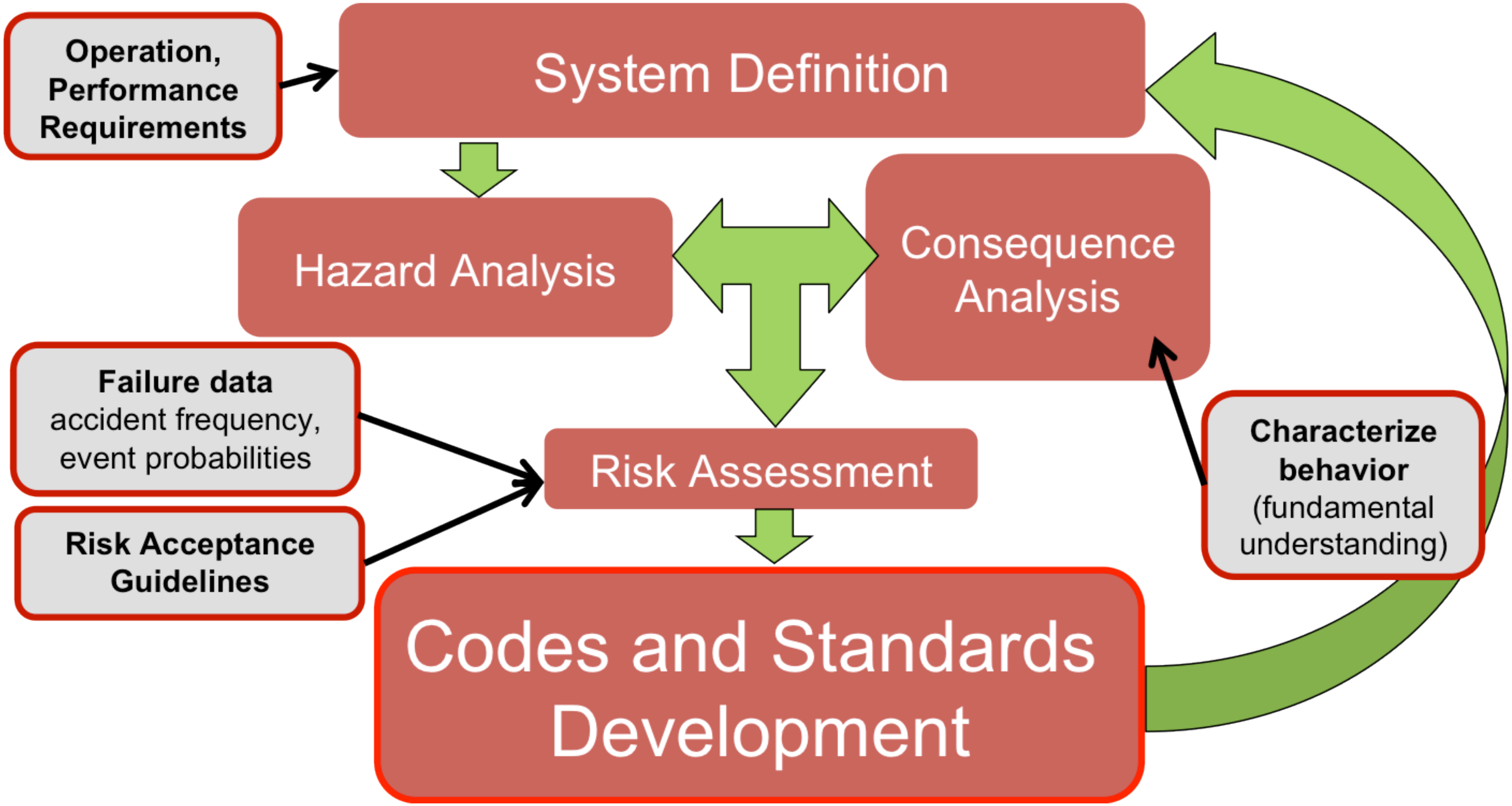
Accidents & Overpressure

Consequence calculation (FAR/AIR)

- Potential Loss of Life (PLL) is expressed as follows:
- $PLL = \sum_n \sum_j (f_{nj} \cdot \ c_{nj})$
  - Where f_nj is the frequency of an accident scenario n with (personnel) consequence j
  - And c_nj is the expected number of fatalities for accident scenario n with (personnel) consequence j. n is the total number of accident scenarios in all ESDs. J is the total of personnel consequence types.

- $FAR = \frac{PLL \cdot 10^8}{Exposed\ hours} = \frac{PLL \cdot 10^8}{N_{staff} \cdot 8760}$
- $AIR = H \cdot FAR \cdot 10^{-8}$
- Where N_staff is the average number of personnel in the facility and H is the number of hours spent in the facility, per

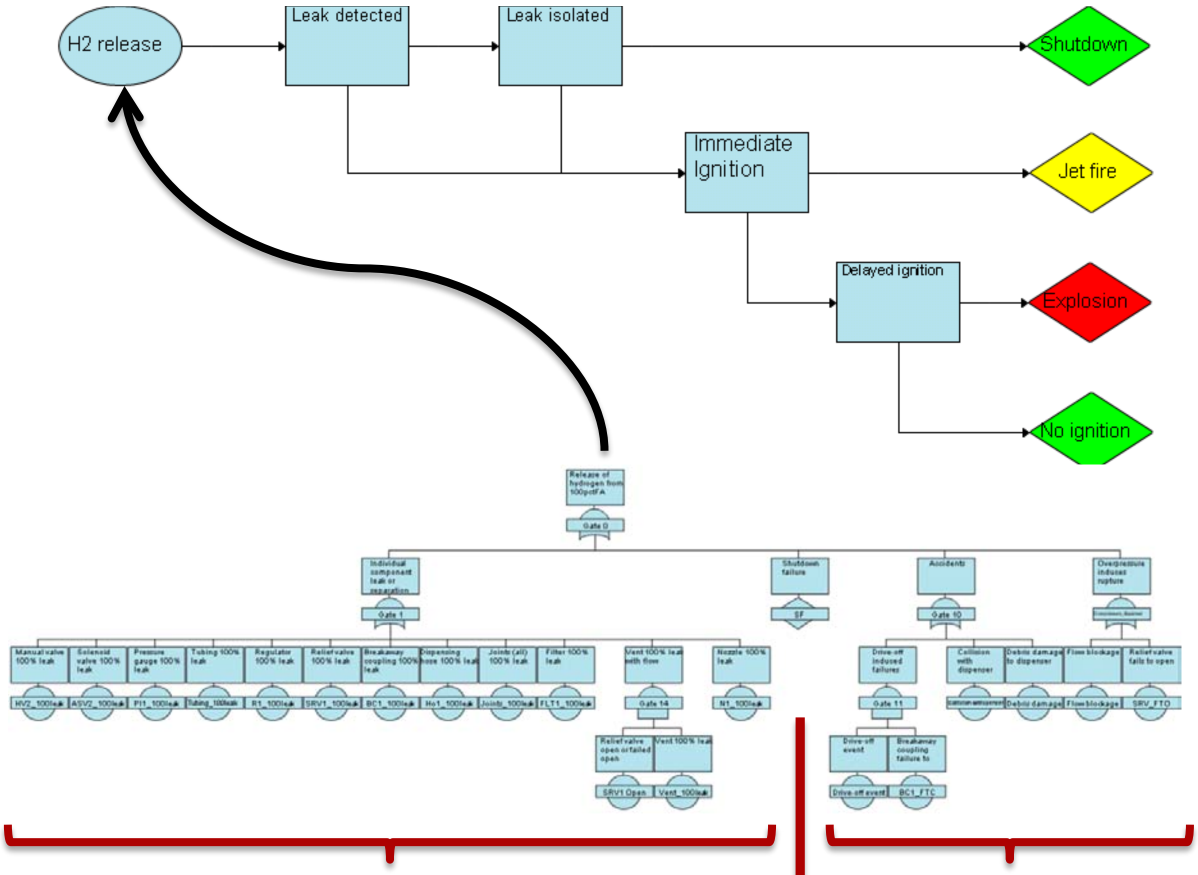
QRA Process for C&S development



Scenarios (Hard-coded in QRA tool)

Release scenarios & Causes:

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



Individual component leaks

Shutdown failures

Accidents & Overpressure

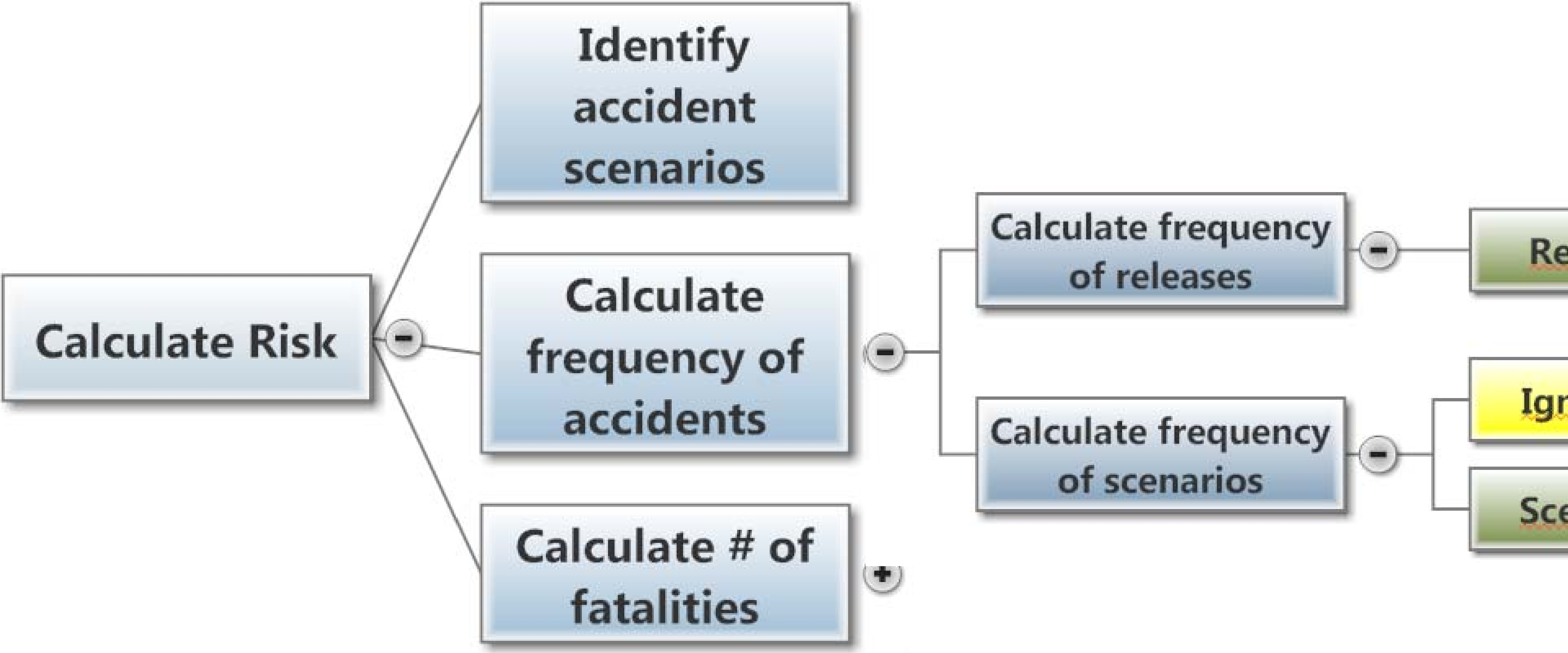
Hazards considered:

- Thermal radiation
- Overpressure

Hazards excluded:

- Asphyxiation
- Debris

Modules in QRA tool



Calculate Risk

Identify accident scenarios

Calculate frequency of accidents

Calculate # of fatalities

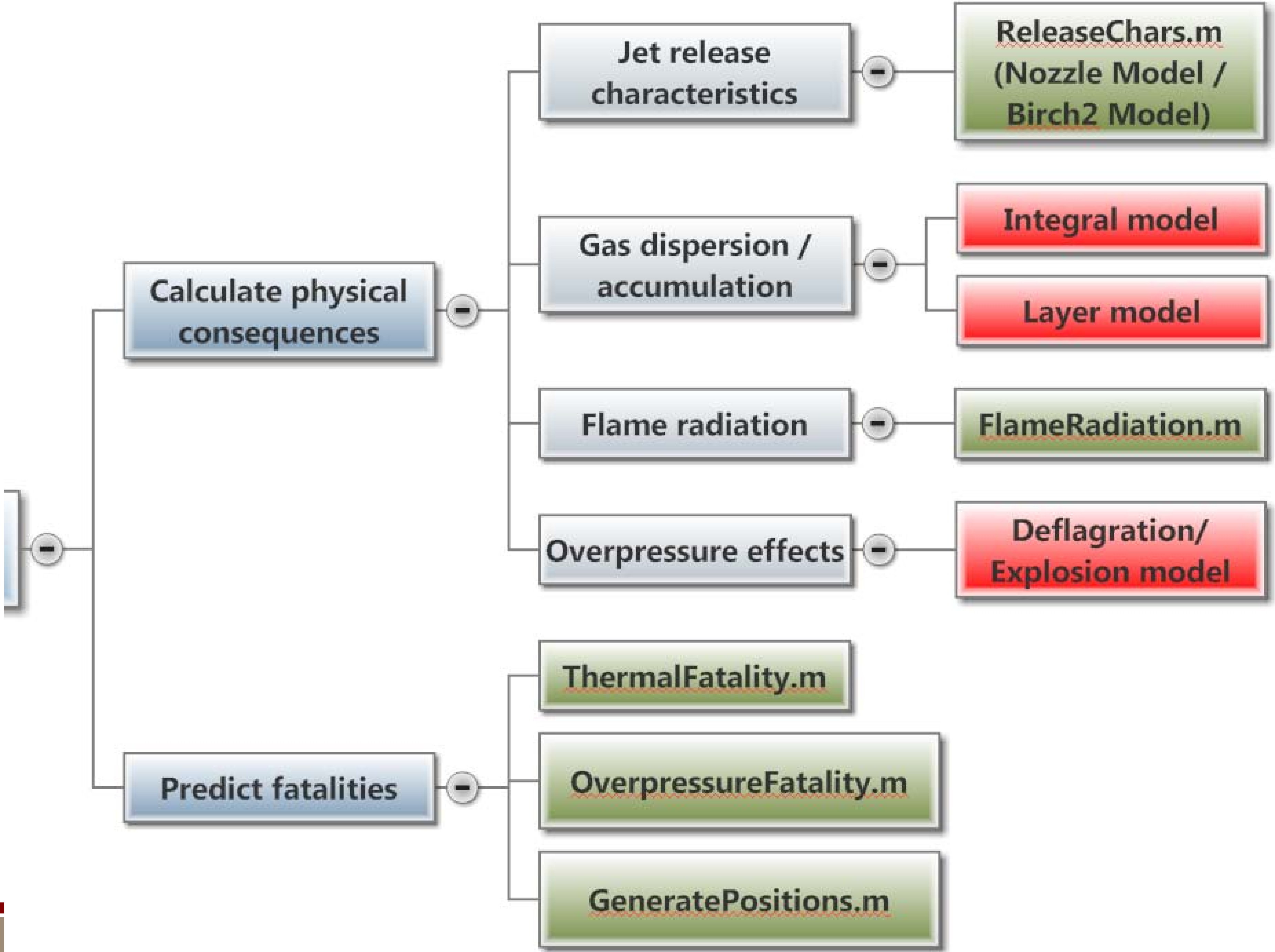
Calculate frequency of releases

Calculate frequency of scenarios

Re

Ign

Sce



Calculate physical consequences

Jet release characteristics

ReleaseChars.m (Nozzle Model / Birch2 Model)

Gas dispersion / accumulation

Integral model

Layer model

Flame radiation

FlameRadiation.m

Overpressure effects

Deflagration/ Explosion model

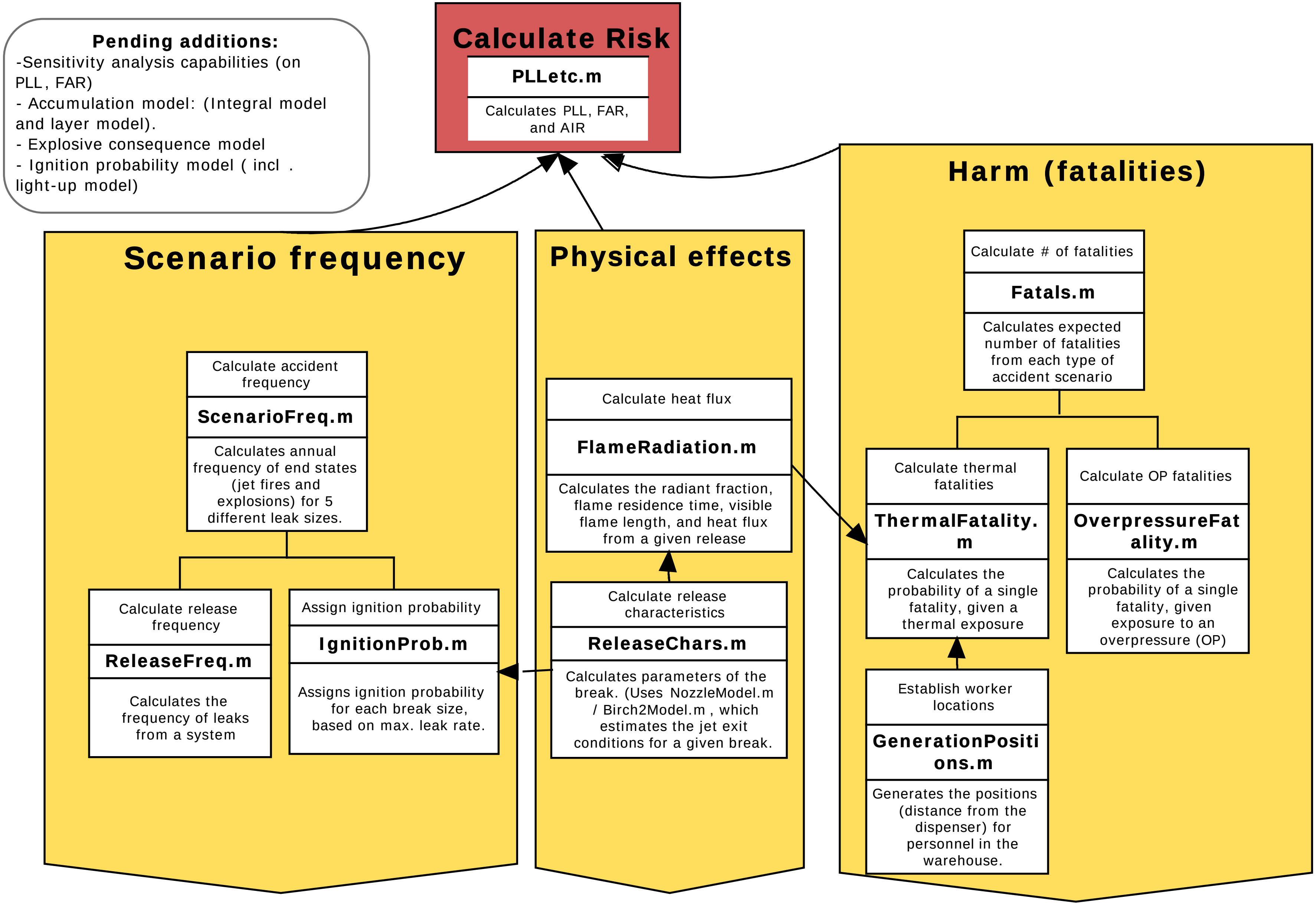
Predict fatalities

ThermalFatality.m

OverpressureFatality.m

GeneratePositions.m

QRA Tool modules



Pending additions:

-Sensitivity analysis capabilities (on PLL, FAR)

- Accumulation model: (Integral model and layer model).
- Explosive consequence model
- Ignition probability model (incl . light-up model)

Calculate Risk

PLLetc.m

Calculates PLL, FAR, and AIR

Scenario frequency

Calculate accident frequency

ScenarioFreq.m

Calculates annual frequency of end states (jet fires and explosions) for 5 different leak sizes.

Calculate release frequency

ReleaseFreq.m

Calculates the frequency of leaks from a system

Assign ignition probability

IgnitionProb.m

Assigns ignition probability for each break size, based on max. leak rate.

Physical effects

Calculate heat flux

FlameRadiation.m

Calculates the radiant fraction, flame residence time, visible flame length, and heat flux from a given release

Calculate release characteristics

ReleaseChars.m

Calculates parameters of the break. (Uses NozzleModel.m / Birch2Model.m , which estimates the jet exit conditions for a given break.

Harm (fatalities)

Calculate # of fatalities

Fatals.m

Calculates expected number of fatalities from each type of accident scenario

Calculate thermal fatalities

ThermalFatality.m

Calculates the probability of a single fatality, given a thermal exposure

Calculate OP fatalities

OverpressureFatality.m

Calculates the probability of a single fatality, given exposure to an overpressure (OP)

Establish worker locations

GenerationPositions.m

Generates the positions (distance from the dispenser) for personnel in the warehouse.

Safety

- Dictionary.com says:
    - “the state of being safe; freedom from the occurrence or risk of injury, danger, or loss. “
    - Safe:
        - 1. secure from liability to harm, injury, danger, or risk: a safe place.
        - 2. free from hurt, injury, danger, or risk: to arrive safe and sound.
        - 3. involving little or no risk of mishap, error, etc.: a safe estimate.
        - 4. dependable or trustworthy: a safe guide.
        - 5. careful to avoid danger or controversy: a safe player; a safe play.

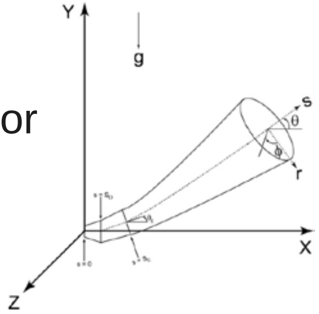
What are you trying to predict? (What does “safety” mean?)

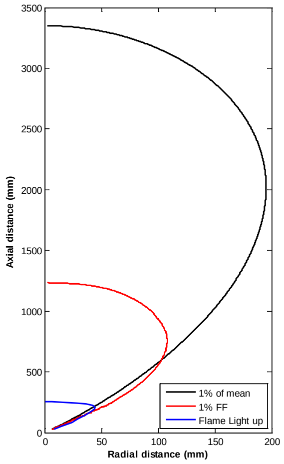
- Human injury or fatality?
  - Individual vs. Group
  - Workers and/or Members of the public
- Accident occurrence?
  - Fire (how big?)
  - Deflagation or explosion?
- Economic loss
- Environmental damage – can be expressed in terms of time required to recover damage to ecosystem

Summary

Release Characteristics

- H_2 jet integral model developed & validated
- Source models developed for LH2 & choked flow inputs
- Improved intermittency & scalar PDF prediction



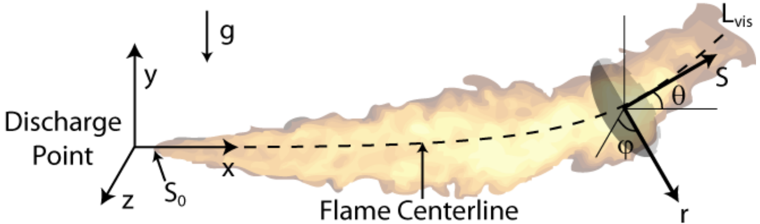


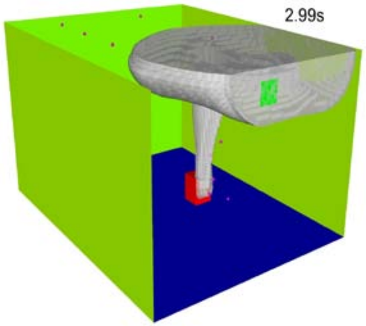
Ignition/Flame Light-up

- Flammability Factor verified for ignition prediction
- Light-up boundaries identified

Flame Radiation

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





Combustion within Enclosures

- Ventilated deflagration overpressure explored experimentally and numerically
- Engineering model framework developed