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Engineering a Fire Safe World

Application of Quantitative Risk Assessment (QRA) for Performance-Based Permitting of Hydrogen Fueling Stations

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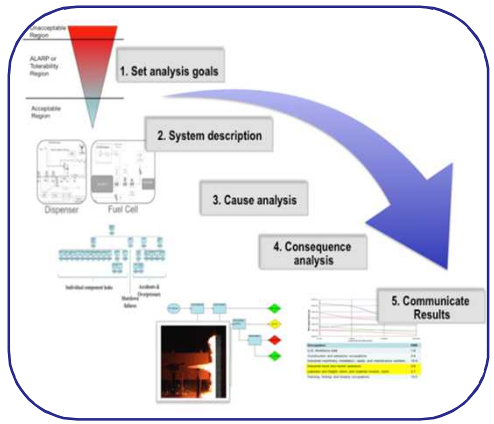
Program Objective and Approach

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

Apply risk assessment techniques in innovative hydrogen technologies

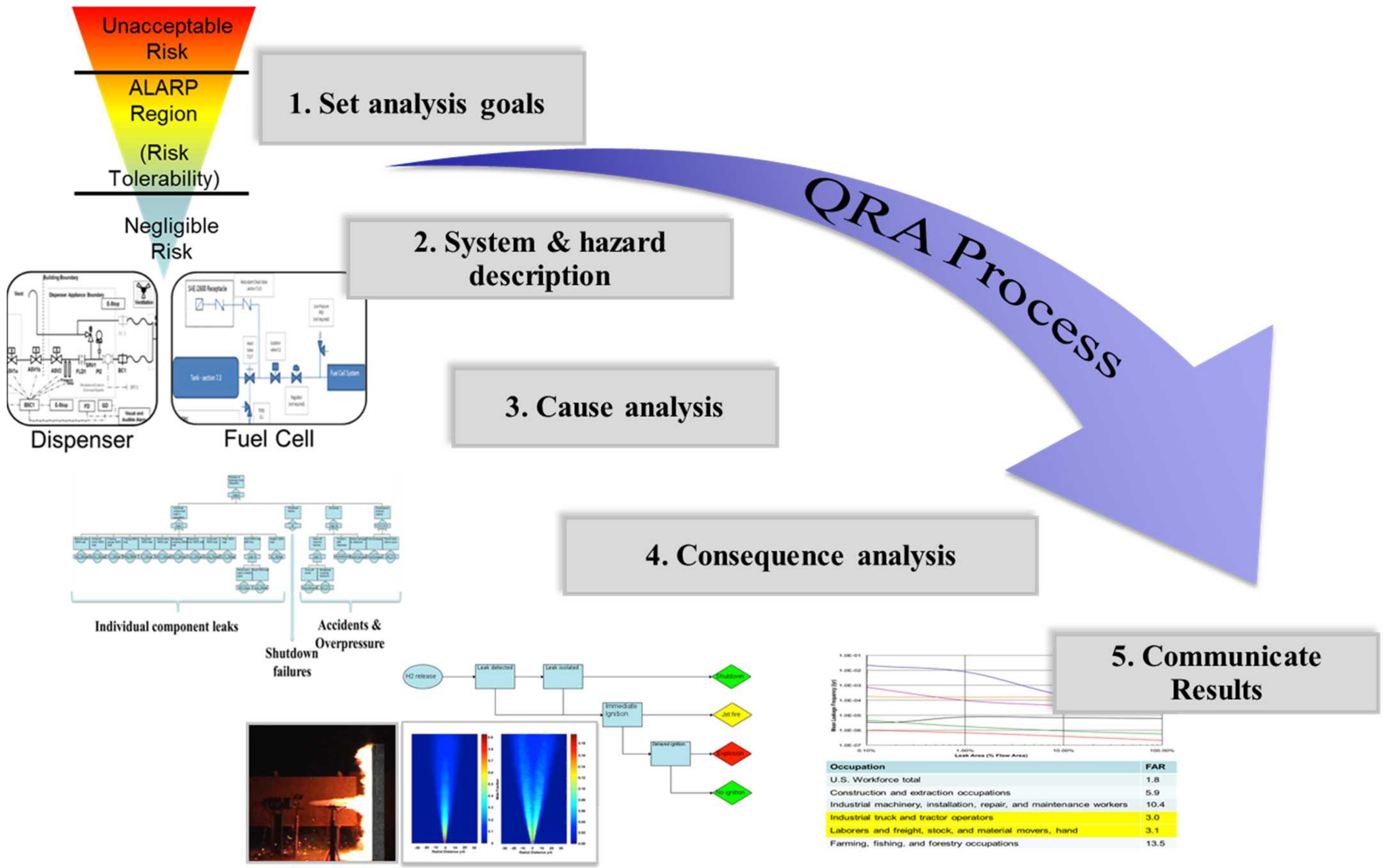


Develop integrated algorithms for conducting QRA for H_2 facilities and vehicles

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

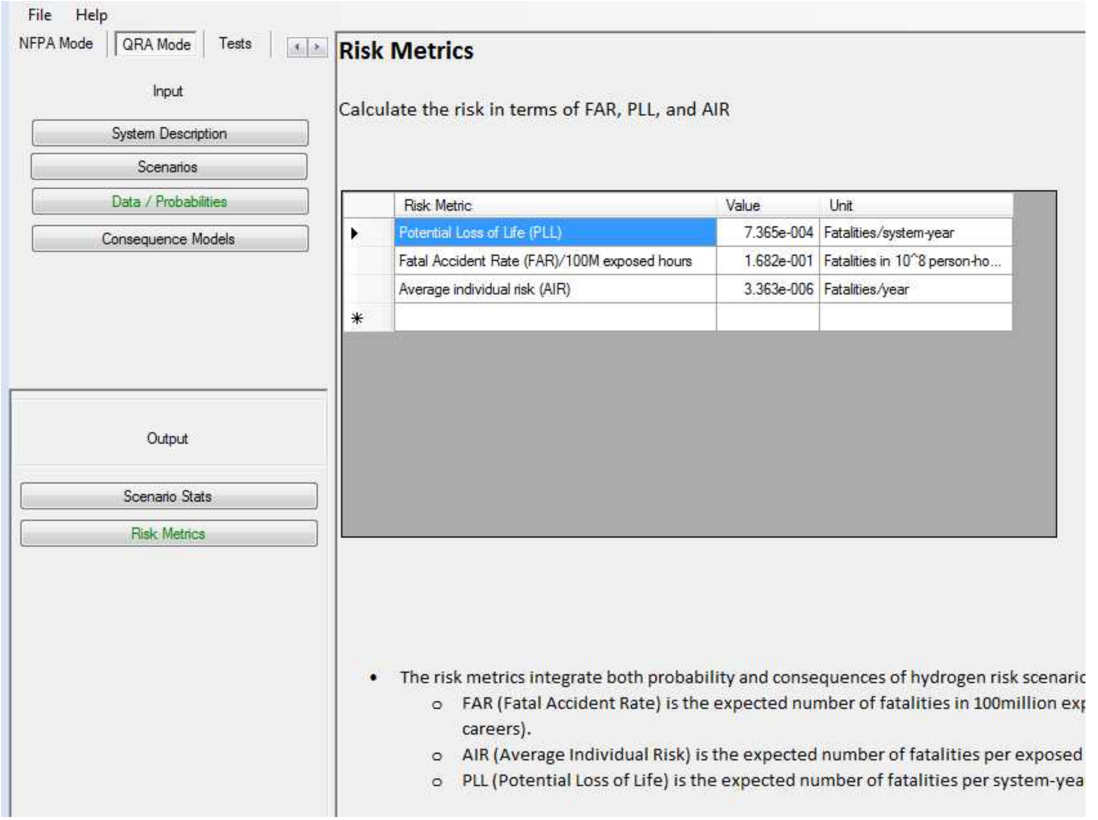
Enabling QRA tools for H2 industry

QRA Approach Integrates Deterministic and Probabilistic Models



QRA toolkit integrates state-of-the-art H2 models

- All relevant hazards (thermal, mechanical, toxicity)
- H2 probabilistic models and systems data
- H2 phenomena (gas release, ignition, heat flux, overpressure)



Metrics Currently Supported

Calculates 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

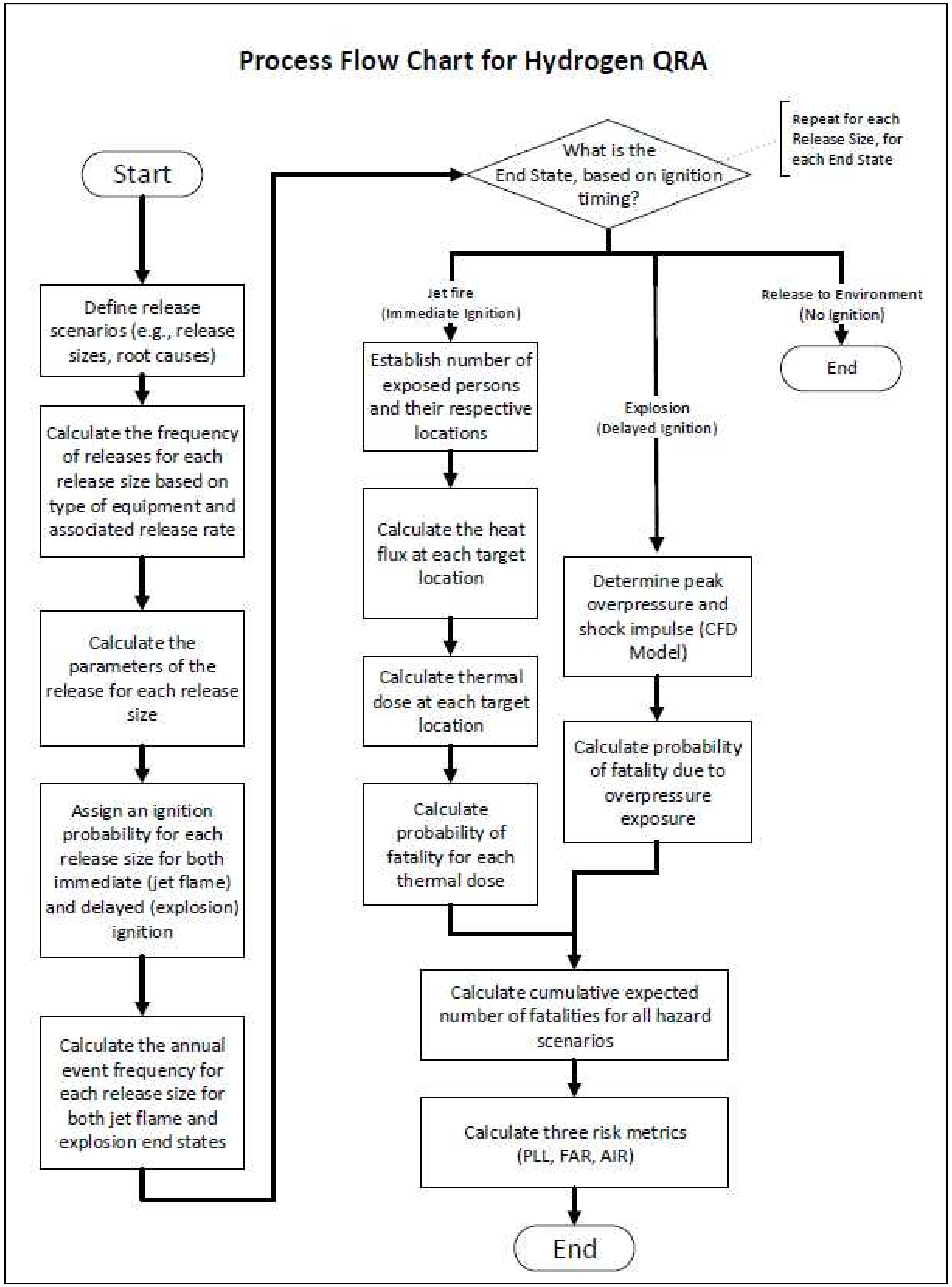
And physical behavior of:

- Hydrogen jets
  - Width, velocity, density, …
- Jet fires
  - Flame length, heat flux, …
- Deflagrations (coming soon)
  - Ignitable volume, overpressure, …

Flow Chart

Integrates best available probabilistic and deterministic models for:

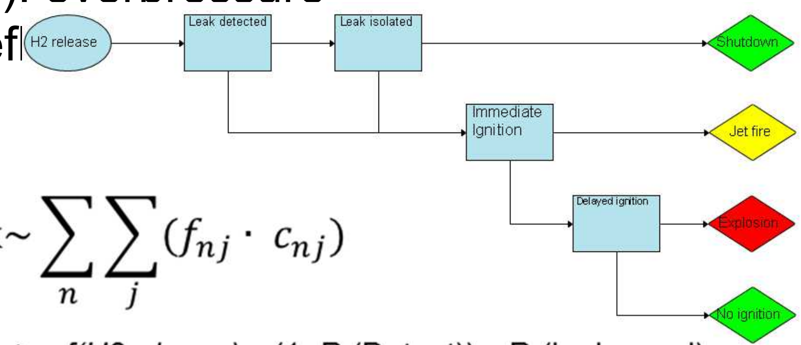
- Component failure
- Ignition occurrence
- Gas release
- Gas dispersion
- Jet flames
- Deflagration / detonation
- Harm to humans and structures



Modules: Cause & Harm Models

Accident sequences

- Hazards considered: Thermal effects (jet fire), overpressure (defl



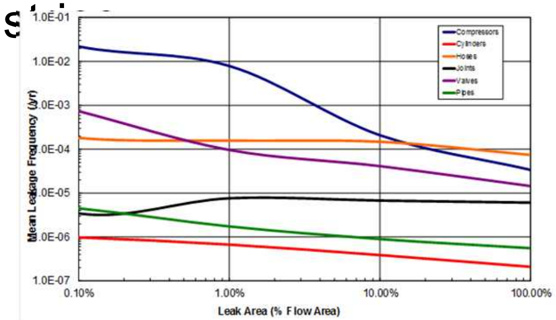
$$Risk \sim \sum_n \sum_j (f_{nj} \cdot c_{nj})$$

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

Release frequency

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

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



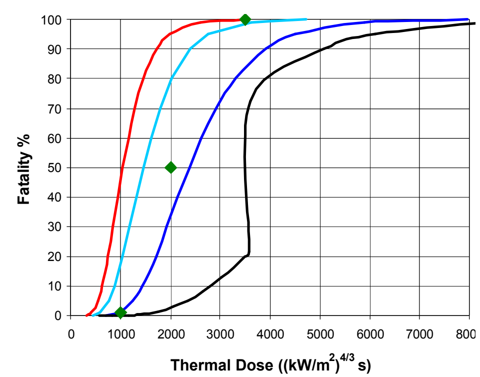
Ignition probability

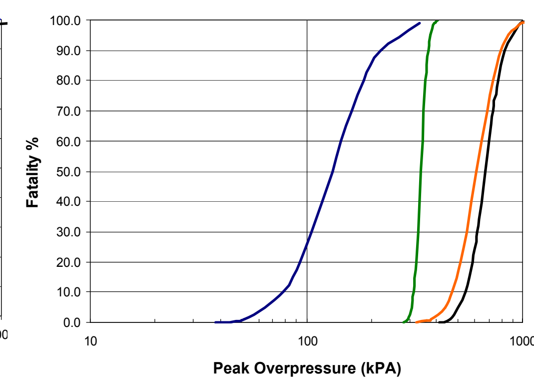
- Extrapolated from methane ignition probabilities
- Flow rate calculated using *Release Characteristics* module

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

Harm models

- Probability of fatality from exposure to heat flux and overpressures – multiple options

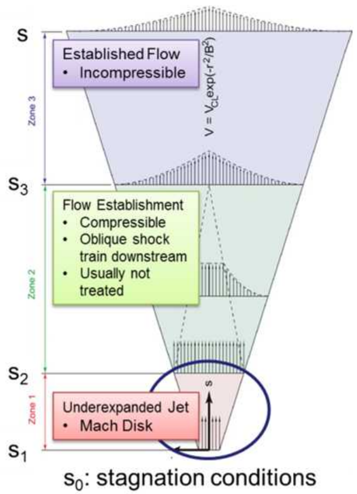


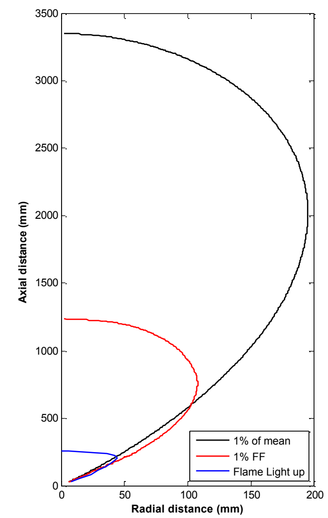


Physics Modules: Behavior & Consequence

Release Characteristics

- H_2 jet integral model developed & validated
- Source models developed for LH2 & choked flow inputs



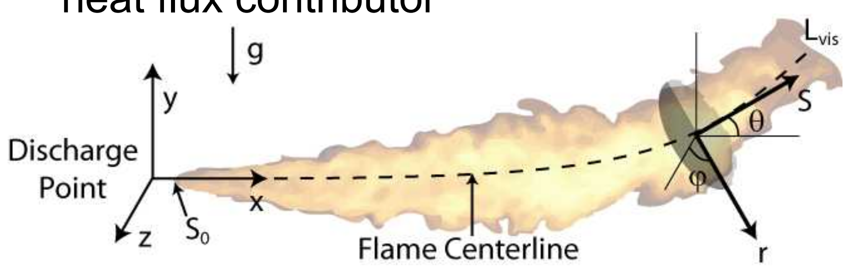


Ignition/Flame Light-up *(pending addition)*

- Flammability Factor verified for ignition prediction
- Light-up boundaries identified
- Next: sustained flame prediction

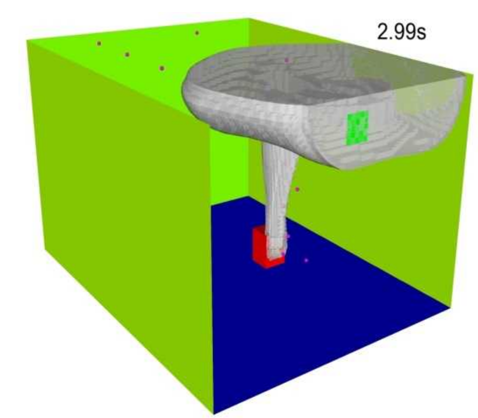
Flame Radiation

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



Deflagration within Enclosures

- Ventilated deflagration overpressure explored experimentally and computationally
- Current QRA module requires CFD results.
- Engineering model framework pending



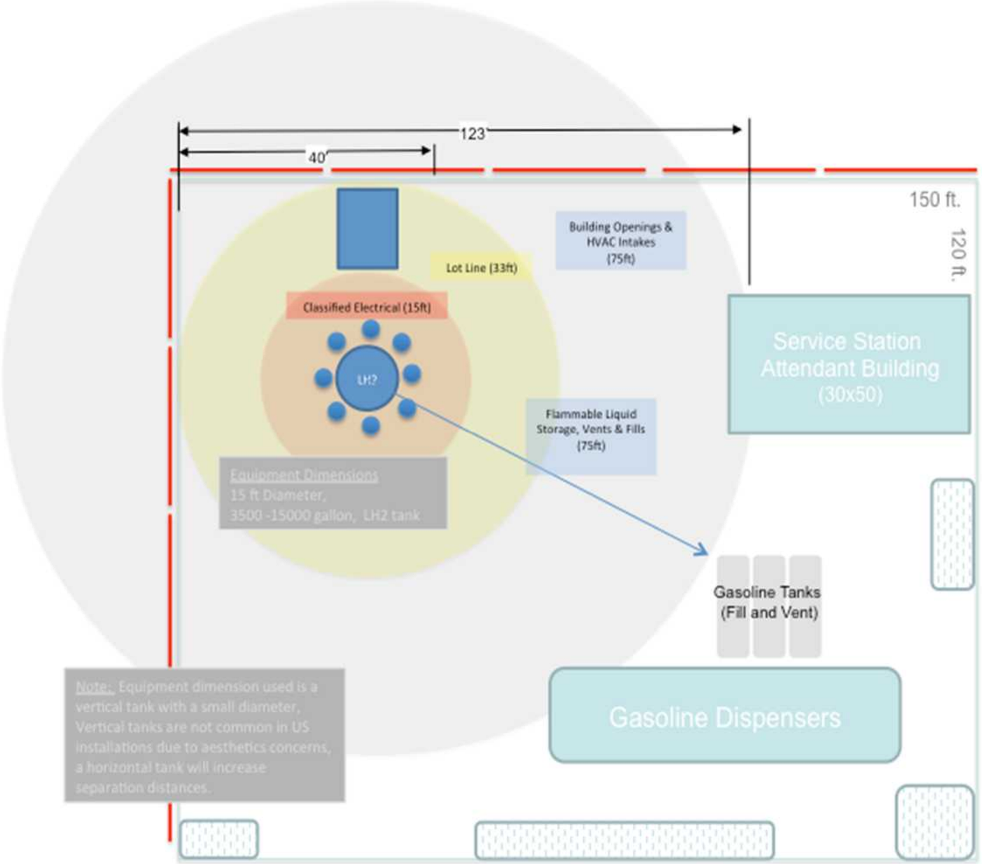
Activity 1: Pilot Implementation

First Iteration - **Baseline**

- QRA Toolkit is being used to calculate risk values for the Performance Criteria on a typical station, fully compliant with prescriptive codes

- This will provide a Baseline for risk values and enable easy comparison of the changes made in the second iteration

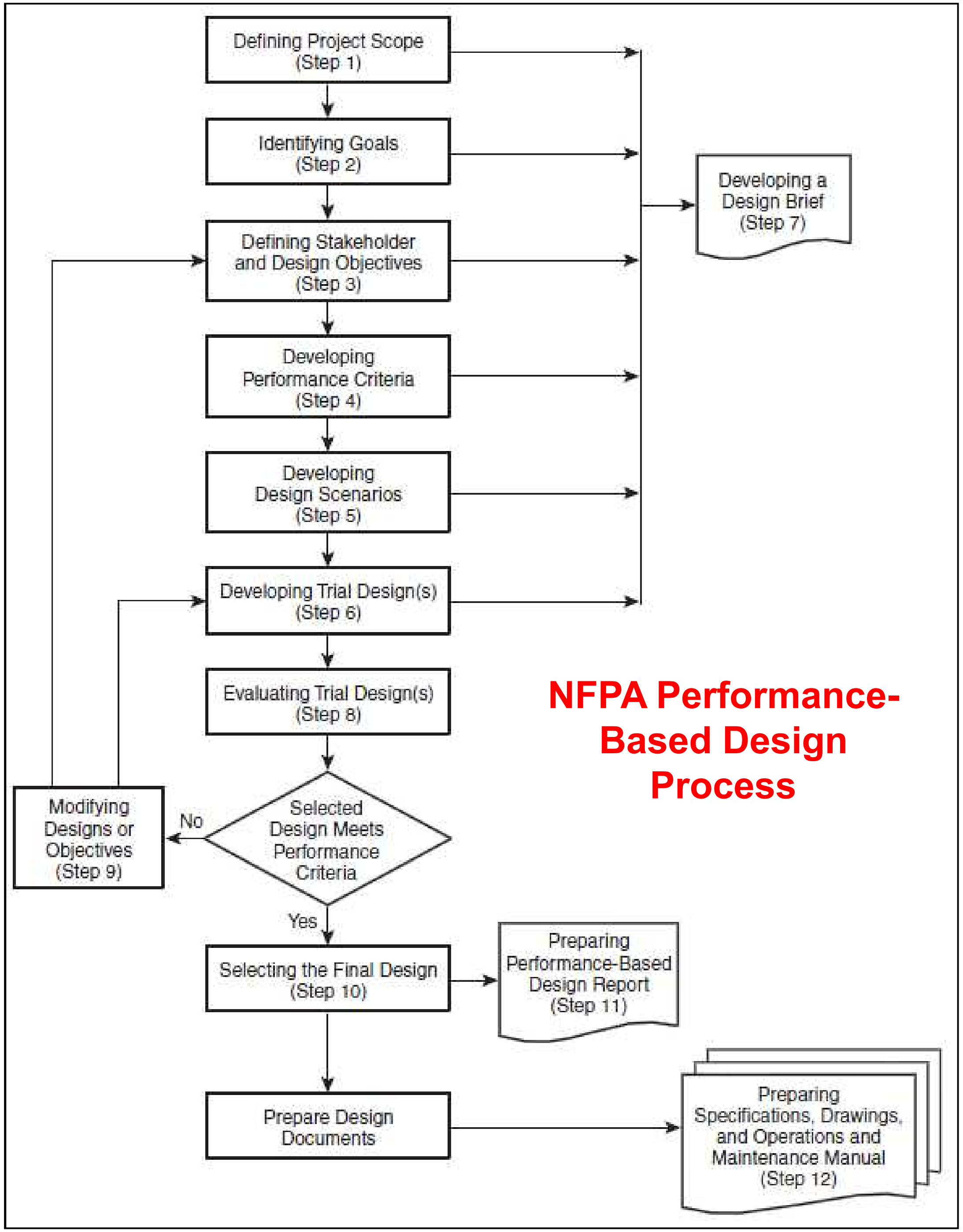
- The AIR value is used for comparison purposes



Activity 1: Pilot Implementation

Second Iteration

- Industry partner selected key parameters to shift from the prescriptive requirements to optimize the design for implementation
- Risk values are being recalculated and mitigating or off-setting measures are being explored that move toward risk-equivalent values for AIR
- Performance-based design and mock permitting documents will be submitted to industry experts and experienced AHJs for vetting



Activity 2: Field Validation

- One element of optimization of the station design will be incorporated in to a real world retail refueling station planned by our industry partner, Linde. Separation distance to non-classified electrical equipment (car wash vacuums) are the target element currently.

- Performance-based design and permitting documents will be submitted to the actual AHJ for the site in California.

Design Brief Elements: Project Scope and Goals

- Scope

  Design a retail hydrogen refueling station utilizing liquid hydrogen (LH2) storage tank and associated components. This station is built on an existing gasoline fuel site located in an urban or suburban city in the State of California.

- Goal

  Compare a fully code-compliant, prescriptive-based fueling station design with a fueling station that was designed using a performance-based approach utilizing QRA

NFPA 2 Performance-Based Design: Explosion Scenarios

	Pressure Vessel Burst	Hydrogen Deflagration	Hydrogen Detonation
Scenario Description	5.4.3.1: Pressure vessel ruptures	5.4.3.2: Deflagration of a hydrogen-air or hydrogen-oxidant mixture within large process equipment	5.4.3.3: Detonation of a hydrogen-air or hydrogen-oxidant mixture within a process vessel or within piping containing hydrogen
Outdoor Fueling Station Scenario	Gaseous H2 vessel ruptures due to relief valve failure	Deflagration within/nearby the vaporizer	Unintended release forms localized H2/air mixture that detonates
Toolkit Inputs	Calculate local blast wave impulse, needs to be added to Toolkit	Calculate local blast wave impulse, needs to be added to Toolkit	Calculate local blast wave impulse, needs to be added to Toolkit

NFPA 2 Performance-Based Design: Hazardous Materials Scenarios

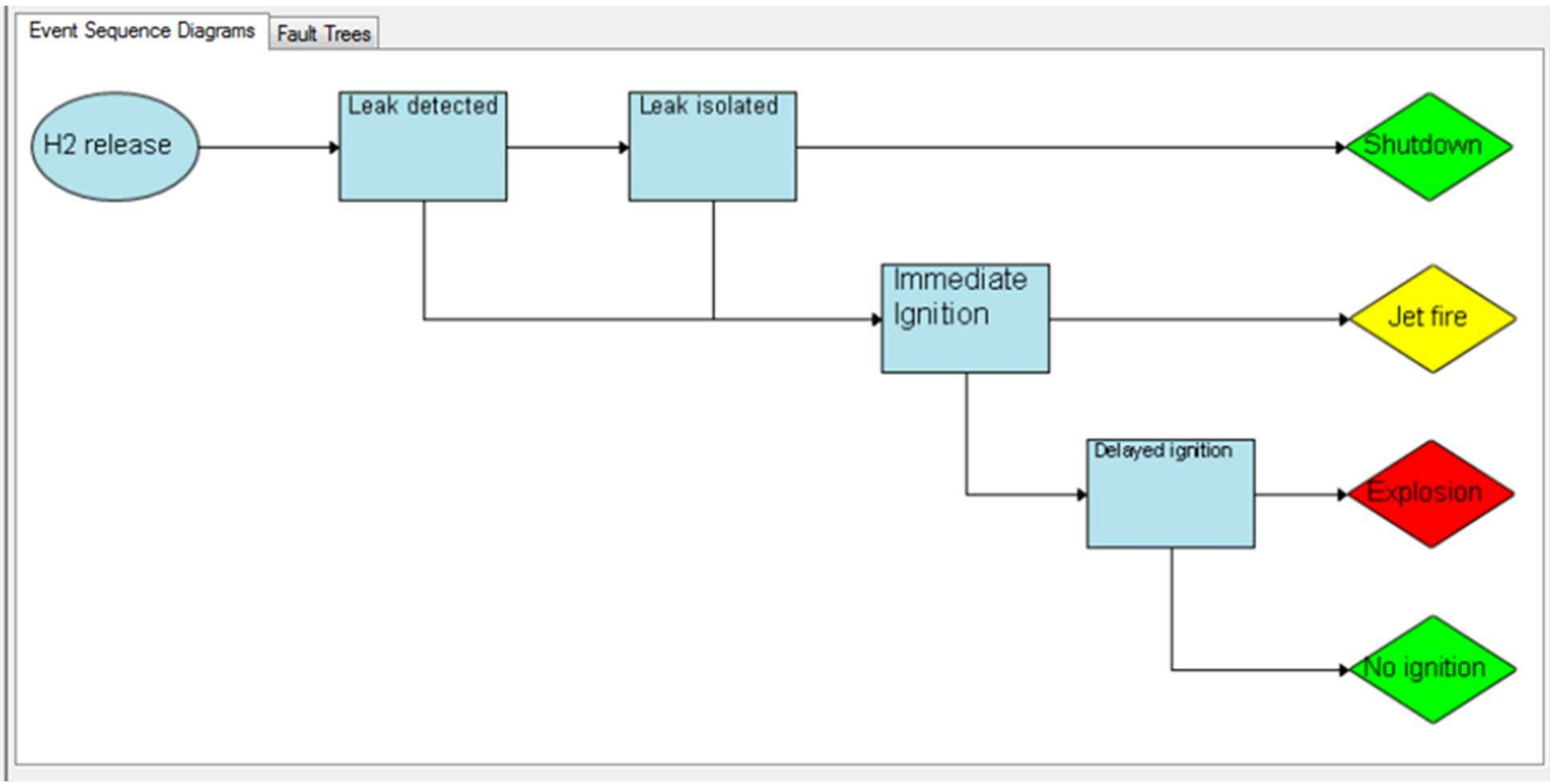
	Unauthorized Release	Exposure Fire	External Factor	Discharge with protection system failure
Scenario Description	5.4.4.1: Unauthorized release from a single control area	5.4.4.2: Exposure fire on a location where hydrogen is being stored, used, handled or dispensed	5.4.4.3: Application of an external factor that is likely to result in a fire, explosion, toxic release or other unsafe condition	5.4.4.4: Unauthorized discharge with each protection system independently rendered ineffective
Outdoor Fueling Station Scenario	Unintended release (Jet Fire)	A unrelated car fire at the gasoline dispensing pump	Seismic Event where a pipe bursts (100% Leak Size on largest system pipe)	An unauthorized discharge where the interlock or pressure relief valve fails
Toolkit Inputs	Toolkit, Input Set #2	Discussion and Toolkit, Input Set #3	Toolkit, Input Set #4	Toolkit, Input Set #5

NFPA 2 Performance-Based Design: Scenarios not applicable to an outdoor fueling station

	Egress System	Max Occupant Load with Blocked Exit	Construction in area of building with suppression system out of service
Scenario Description	5.4.2: Design for life safety affecting the egress system	5.4.5.1: Maximum occupant load is in the assembly building and the principal exit/entrance is blocked	5.4.5.2: Fire in an area of the building undergoing construction while remainder of building is occupied. The suppression system has been taken out of service.
Not Applicable Discussion	No egress system since fueling station is outdoors	No assembly occupancies in the vicinity and no exits to block	No partially-occupied buildings with suppression system out of service to analyze

NFPA 2 Performance-Based Design: Fire Scenario

- Description
  - Leak from gaseous side of H2 system, at dispenser. System parameters for largest pipe size, pressure and temperature were used to model the release behavior. QRA considers both an immediate ignition (jet fire) and a delayed ignition (explosion)



Baseline Result for Fire Scenario

- PLL: 5.012×10^{-3} Fatalities/system-year
- AIR: 6.19×10^{-4} Fatalities /year

- Risk Values for US Gasoline Stations
  - Member of Public (Used in NFPA 2): PLL or AIR below 2×10^{-5} fatalities/station-yr
    - Based on 2 fatalities/yr and 100,000 refueling stations in the US
  - Workers: One order of magnitude higher than public risk 1×10^{-4}
- Other Risk Statistics
  - Average Individual Risk (CDC actuarial data 2005)

    = (9117,809 Deaths/Year)/296,748,000 Total U.S. Pop.

    = 4×10^{-4} Deaths/Person-Year (~ 1/2,500 Deaths/Person-Year)

    In any given year, approximately 1 out of every 2,500 people in the entire U.S. population will suffer an accidental death
  - Norwegian Petroleum Directorate guidelines use a total frequency of 5×10^{-4}/yr for all accidents for all safety functions
- Future research activities
  - Better data is needed for ignition probabilities and component failure rates specific to new hydrogen applications.
  - Improved ability to evaluate risk mitigation features

Questions?

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