Trends in Hydrogen Safety Research in the United States

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U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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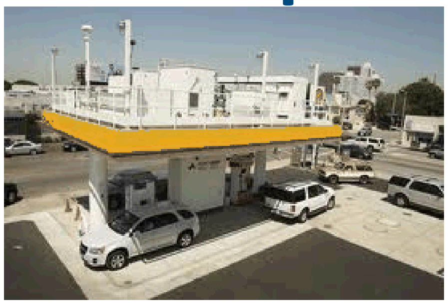
Overview

- *Motivation*
  - Fuel Cell Electric Vehicles (FCEVs)
    - Both passenger vehicles and industrial trucks
- *R&D for Safety, Codes and Standards*
- *Important recent developments*
  - Physics of hydrogen incorporated in fire code
  - ***HyRAM***: Hydrogen Risk Assessment Models
  - CHMC1 standard for materials qualification
- *Future activity and innovations*
  - Quantitative study of liquid hydrogen releases
  - Performance-based risk assessment for infrastructure
  - Methodology to quantify hydrogen-assisted fatigue

Hydrogen vehicles and fueling stations drive the development of codes and standards in the US

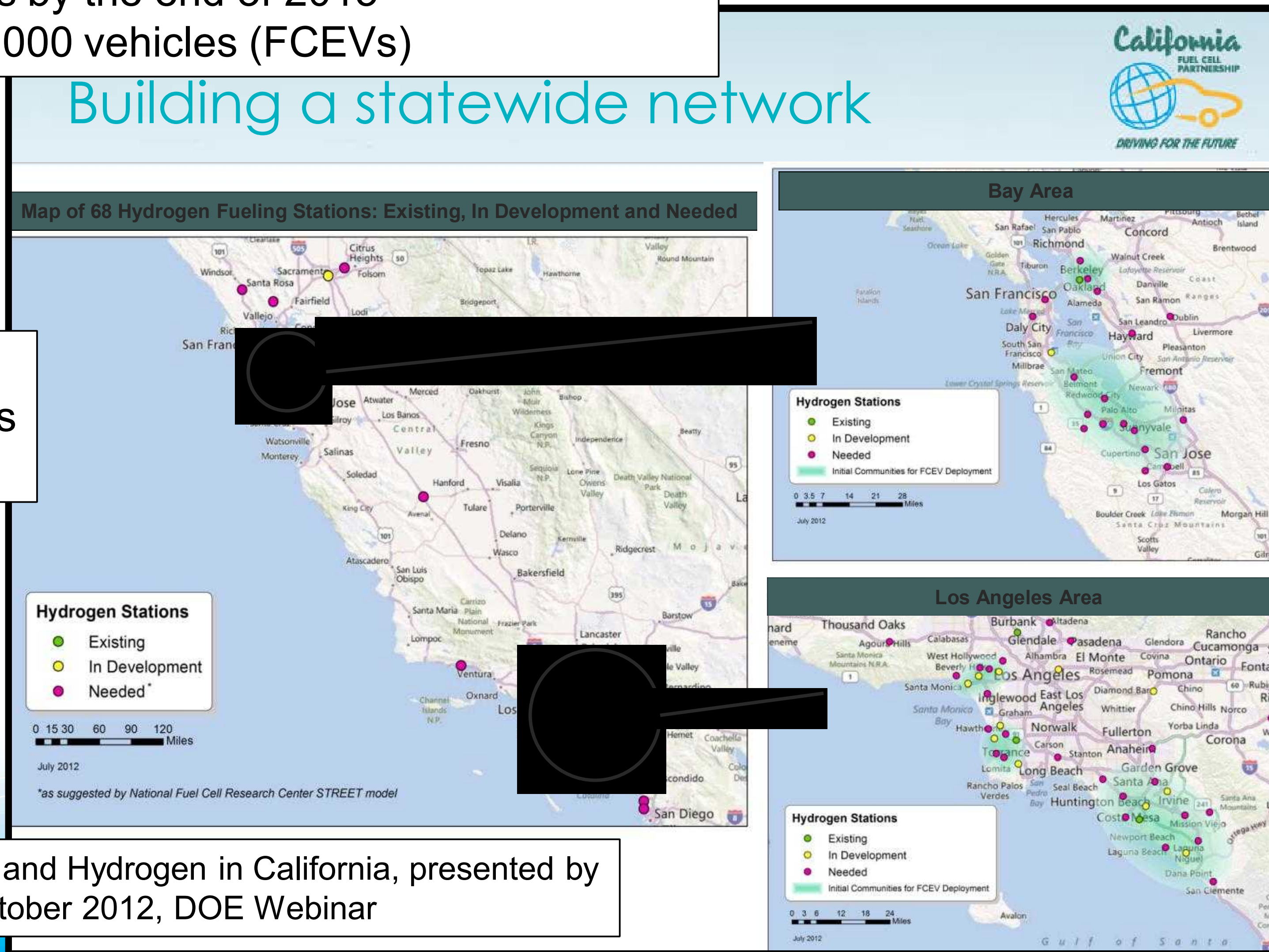


- Growing markets (worldwide estimates)
  - 200-400 light duty vehicles (automobiles on the road)
  - 100-150 heavy duty vehicles (buses, dump-trucks, yard-haulers, etc.)
  - 3,000 industrial trucks (forklifts)
  - >200 fueling stations for buses and automobiles
  - >50 forklift indoor/outdoor fueling sites
- Onboard storage: high-pressure gas at pressure up to 700 bar

California is leading deployment of H2 FCEVs

Goal for California:
- 68 fueling stations by the end of 2015
- serving 5,000-15,000 vehicles (FCEVs)

End of 2012 in CA
- 13 fueling stations
- 312 FCEVs



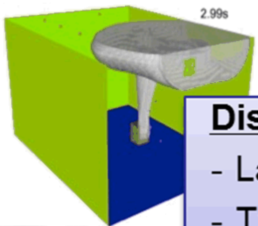
Source: California Fuel Cell Partnership (cafcp.org/roadmap)

Slide taken from: FCEVs and Hydrogen in California, presented by Catherine Dunwoody, October 2012, DOE Webinar

Research and Development for Hydrogen Safety, Codes and Standards

- **Hydrogen Behavior**
  - Quantification of hydrogen releases and the associated consequences
- **Quantitative Risk Assessment (QRA)**
  - Quantification of risk associated with operation of hydrogen infrastructure
- **Materials Compatibility and Suitability**
  - Hydrogen effects on materials and engineering systems
- **Sensors**
  - Low-cost, high-sensitivity detection
- **Fuel Quality**
  - Definition and measurement of impurities in hydrogen

R&D for Hydrogen Safety, Codes and Standards
Hydrogen Behavior



Physics (deterministic)

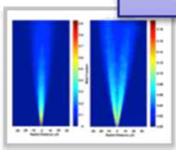
Dispersion Characteristics
- Laminar Flow
- Turbulent jet
- Volumetric rupture
- Enclosure Accumulation

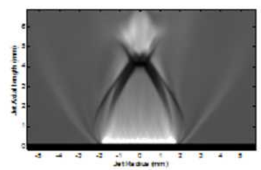
Probability

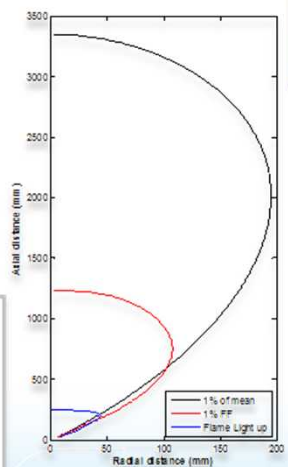
Ignition Probability
- Ignition mechanism
- Mixture ignitability
- Ignition delay/location
- Sustained light-up

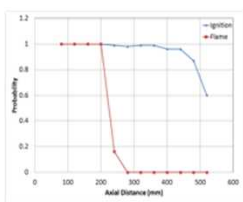
Consequence (deterministic)

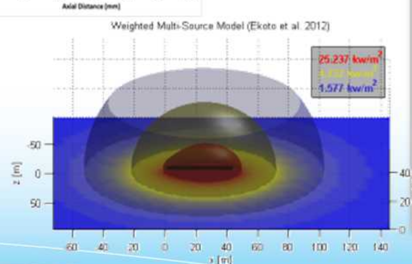
Hazard Characteristics
- Flame radiation
- Overpressure (deflagration/detonation)
- O_2 dilution/depletion





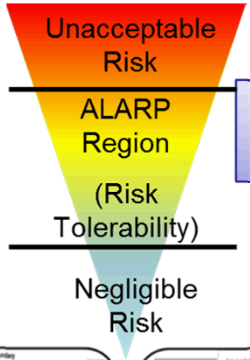






R&D for Hydrogen Safety, Codes and Standards

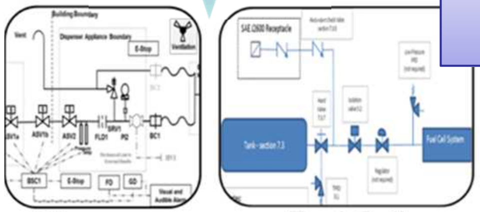
Quantitative Risk Assessment (QRA)



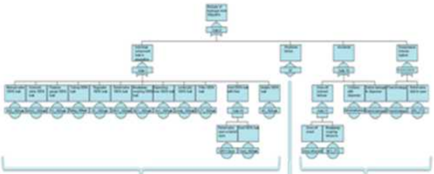
1. Set analysis goals

QRA Process

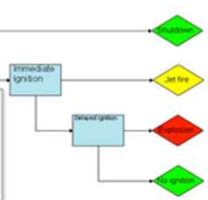
2. System & hazard description

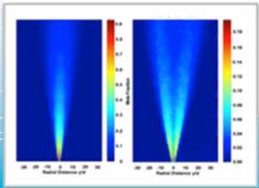


3. Cause analysis

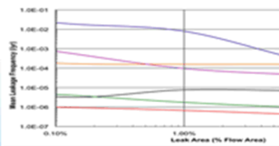


4. Consequence analysis





5. Communicate Results

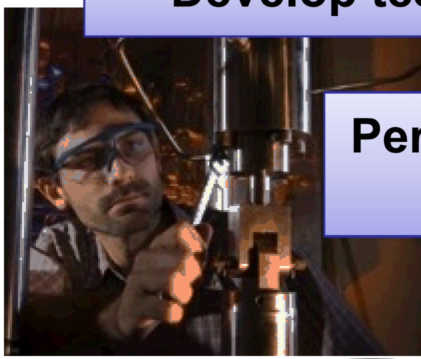


Occupation	FAR
U.S. Workforce total	1.8
Construction and extraction occupations	5.9
Industrial machinery, installation, repair, and maintenance workers	10.4
Industrial truck and tractor operators	3.0
Laborers and freight, stock, and material movers, hand	3.1
Farming, fishing, and forestry occupations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

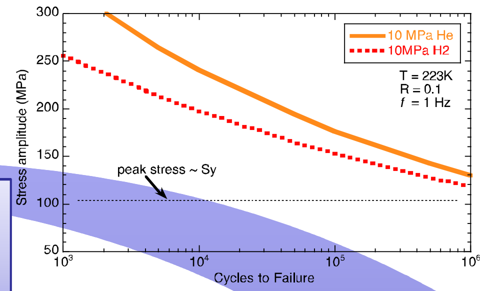
R&D for Hydrogen Safety, Codes and Standards

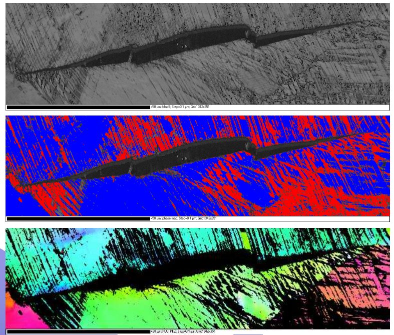
Materials Compatibility and Suitability

Develop test methods

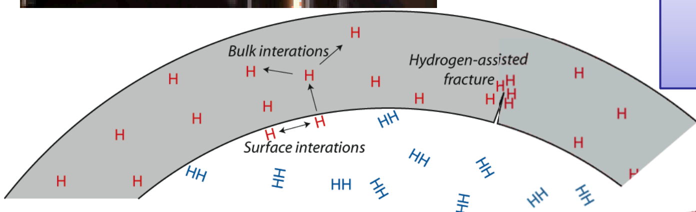


Performance-based testing (compatibility)

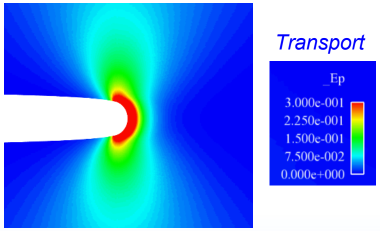


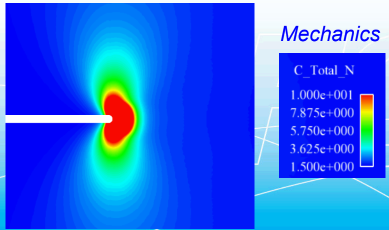


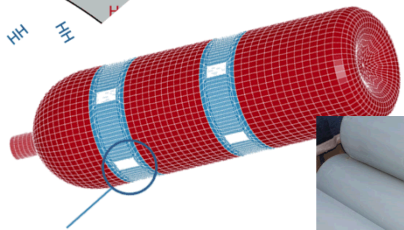
Understanding physics of hydrogen embrittlement

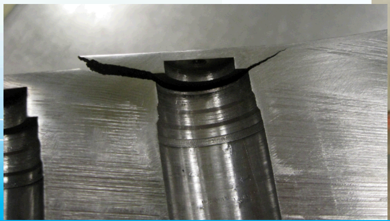


Predictive models









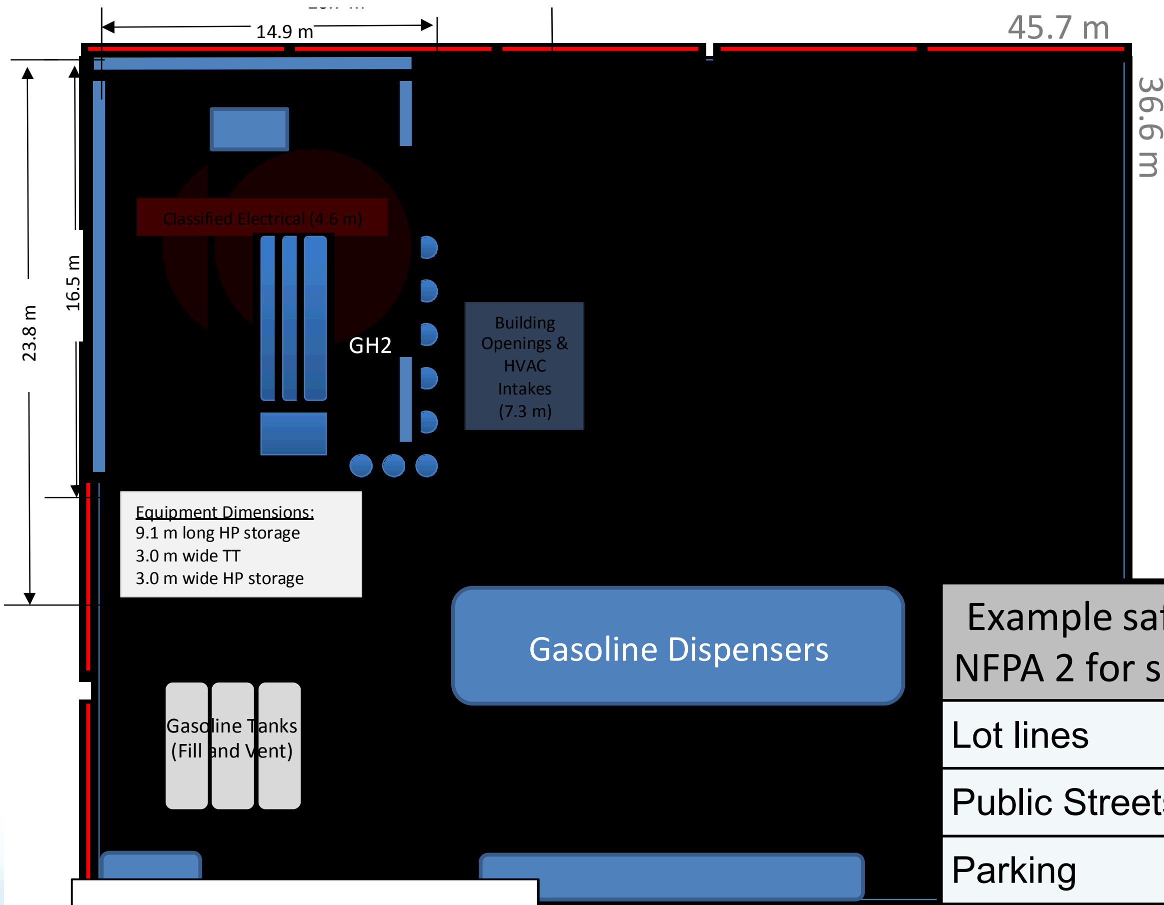
System validation (suitability)

R&D for Hydrogen Safety, Codes and Standards
Materials Compatibility

- Validation of materials and systems testing methods
- Development of testing methodologies to establish environmental and mechanical similitude
  - Performance-based qualification of materials
  - Performance-based qualification of systems and components
- Evaluation of the appropriateness of testing methods
- Trends for pipeline steels
  - Development of phenomenological models of hydrogen-assisted fatigue
  - Prescriptive fatigue behavior of pipeline steels
- Innovative selection of materials for hydrogen service

Hydrogen behavior:

Fire protection code reduced safety distances based on risk-informed, science-based methodology



GH2 storage

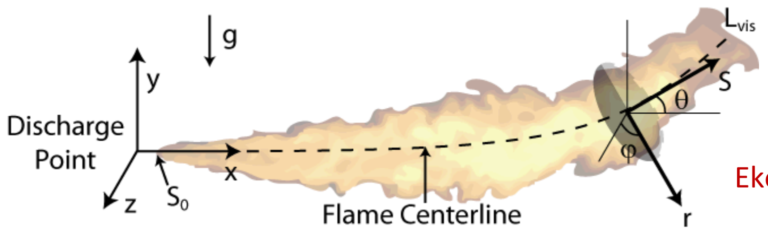
Outcome: **initial safety distances precluded GH2 at existing fueling stations, science-based distances enable the acceptance of GHS at up to 20% of sites**

Harris et al. SAND2014-3416

Example safety distances (m) NFPA 2 for specific boundaries	GH2	LH2
Lot lines	7.3	10.1
Public Streets, Alleys	7.3	10.1
Parking	4.0	22.9
Buildings (sprinkled, fire rated)	3.0	1.5
Building Openings or air intakes	7.3	22.9

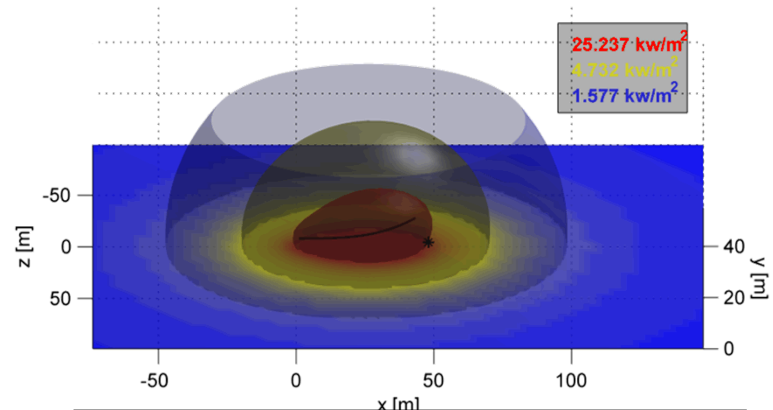
Hydrogen behavior:

Parameterized high-pressure hydrogen flame model combined with integrated heat flux model



Ekoto et al. ICHS 2013

Multi-source flame model:
- **adjusts radiative emitters**
- **accounts for curvature of hydrogen flame**



Predicted heat flux profiles

Notional Nozzle Model	L_f [m]	q_{rad} (Straight) [kW/m²]	q_{rad} (Curved) [kW/m²]
Measurement	45.9	–	23.9
Birch et al. (1984) w/ Abel-Noble	49.3	97.3	29.9
Yüceil & Ötügen (2002) w/ Abel-Noble	44.6	34.8	23.8
Schefer et al. (2007)	44.6	34.8	28.1
Harstad & Bellan (2006) w/ Abel-Noble	52.7	189.8	13.2
Molkov et al. (2009)	49.9	113.2	25.6

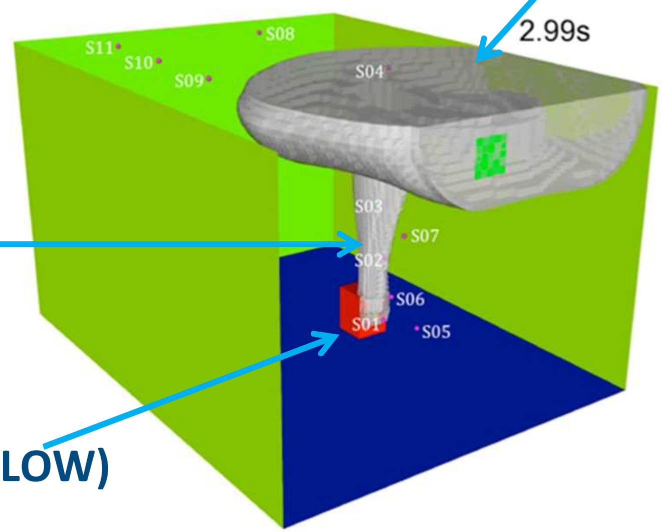
Optimized source model for hydrogen → Yüceil & Ötügen (2002) w/ Abel-Noble

Hydrogen behavior:
Reduced-order models can be combined to predict complex behavior

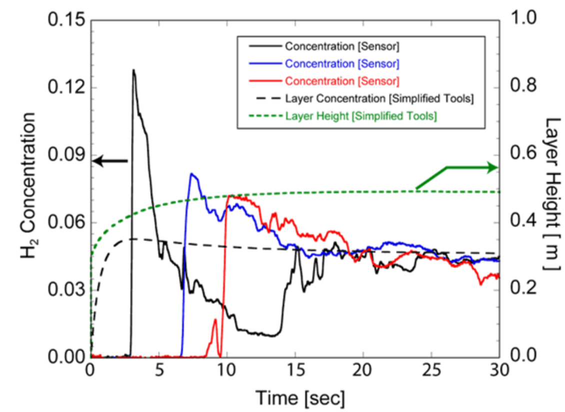
H2 indoor refueling experiments & modeling
Ekoto et al. IJHE 2012
Houf et al. IJHE 2013

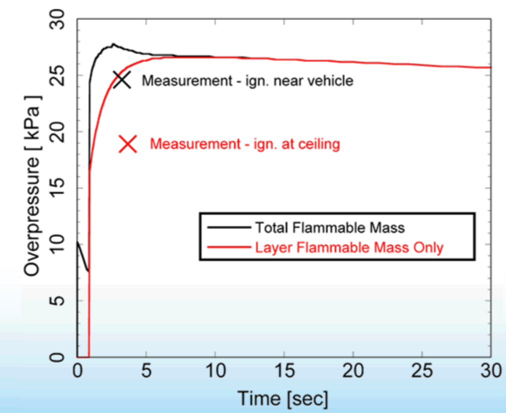
H2 Jet/Plume Model
Houf & Schefer, IJHE 2008

Network Flow Model (NETFLOW)
Winters, SAND 2001-8422



H2 Layer Accumulation Model
Lowesmith et al. IJHE 2009





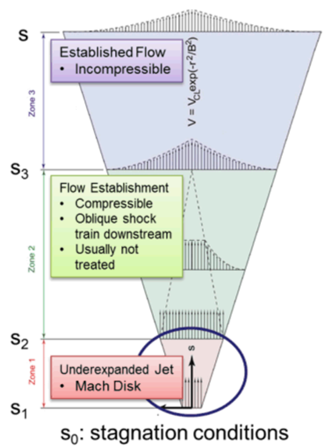
An analytical model for overpressure uses several other physics-based models to quantify the release/dispersion scenario

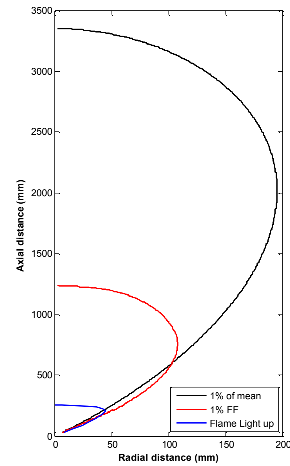
R&D for Hydrogen Safety, Codes and Standards

Hydrogen Behavior

Release Characteristics

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



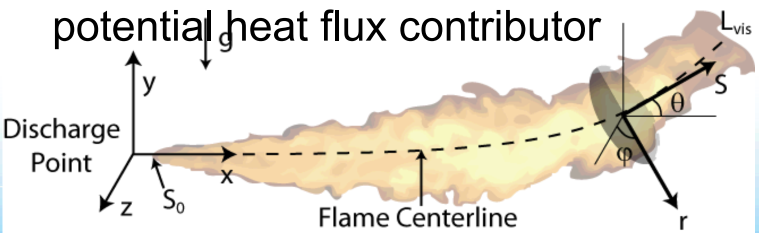


Ignition/Flame Light-up

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

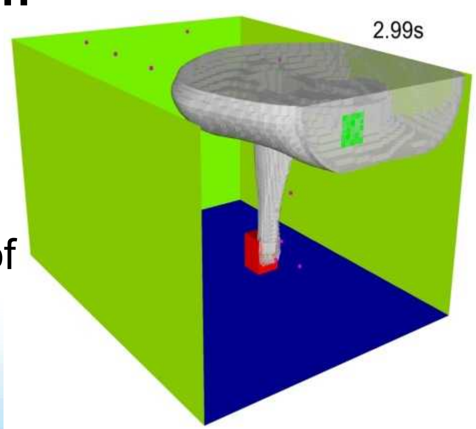
Flame Radiation

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



Deflagration within Enclosures

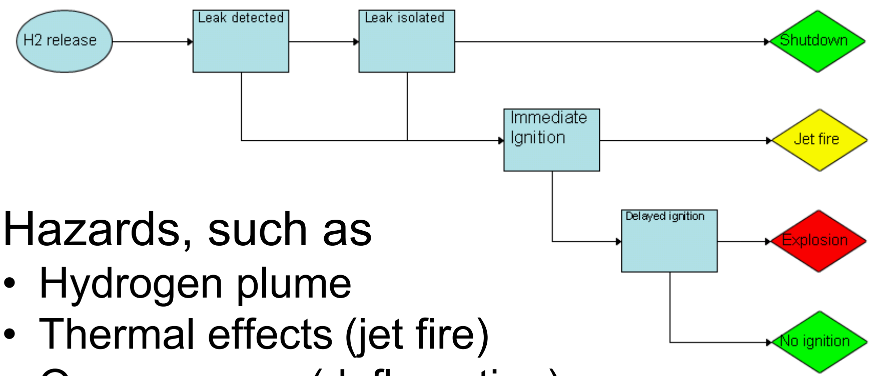
- Overpressure associated with deflagration
- Quantitative role of ventilation



R&D for Hydrogen Safety, Codes and Standards

Risk Assessment

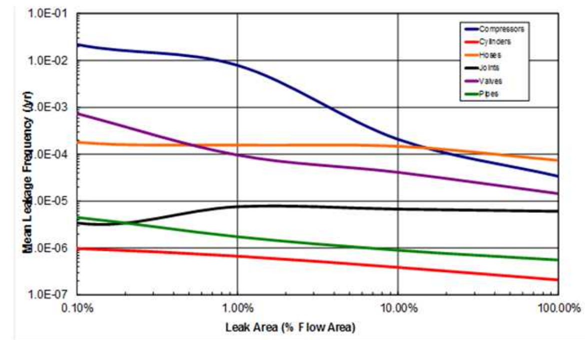
Accident sequences



Hazards, such as

- Hydrogen plume
- Thermal effects (jet fire)
- Overpressure (deflagration)

Release frequency



- Component-specific leak frequency data
- Data developed from available H2 release information and frequency data from other industries

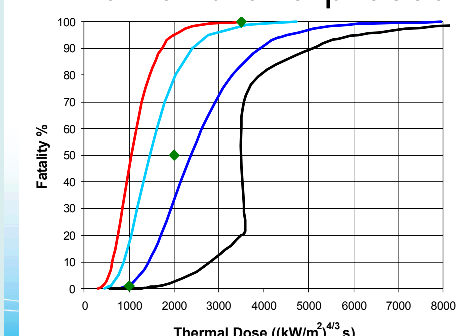
Ignition probability

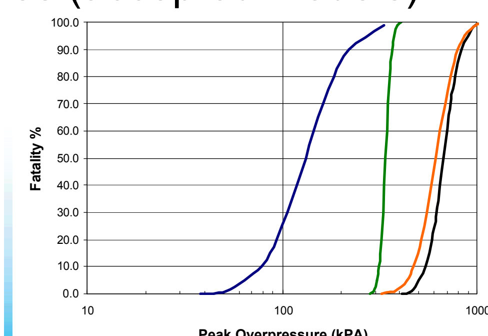
- Extrapolated from methane ignition probabilities
- Intersects with hydrogen behavior models (depends on flow rate)

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

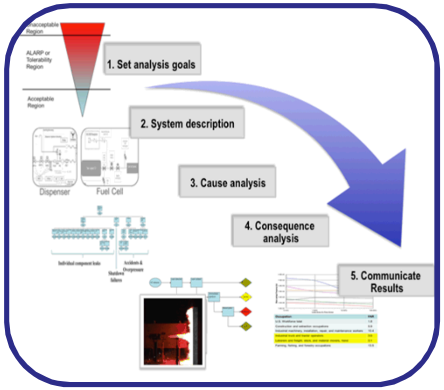
- Probability of fatality from exposure to heat flux and overpressures (accepted models)





Behavior and *risk* models can be integrated to enable consistent (and accepted) risk assessment process

Apply risk assessment techniques in emerging hydrogen technologies



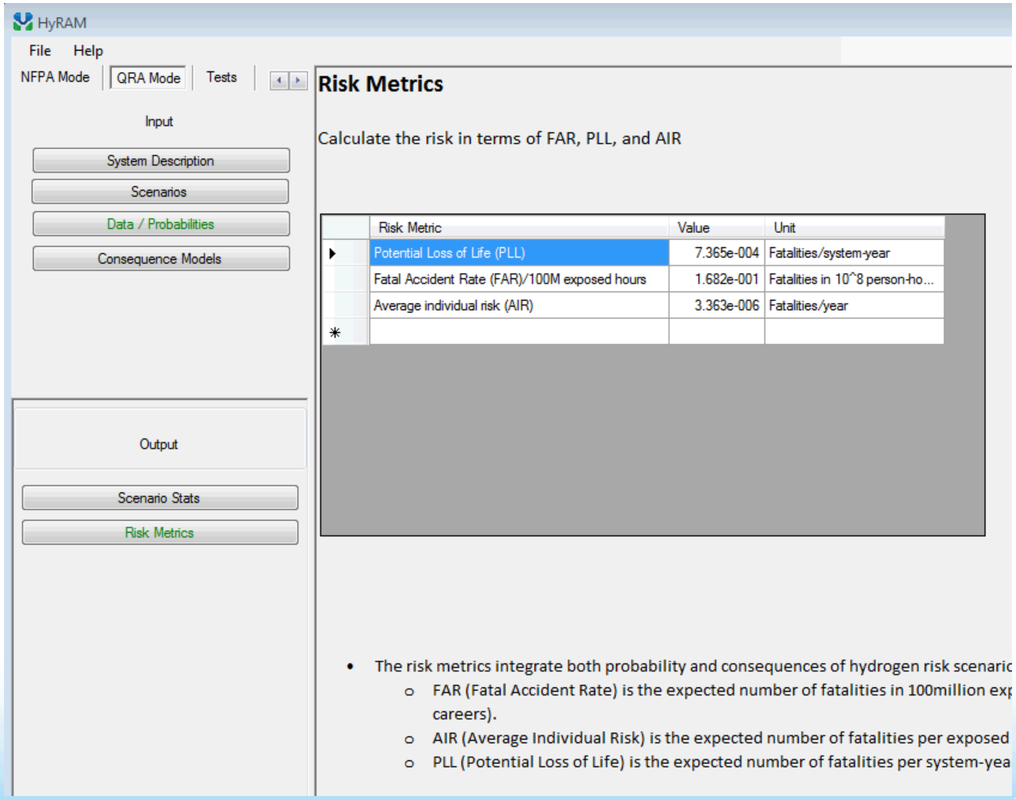
Develop integrated algorithms for conducting QRA for H_2 facilities and vehicles

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

HyRAM
HYDROGEN RISK ASSESSMENT MODELS

Risk assessment:
HyRAM : Hydrogen Risk Assessment Models

- **Goal**: Develop tools to enable industry-led risk assessment
  - Include best-available models:
    - All relevant hazards (thermal, mechanical, toxicity)
    - Probabilistic models & data
    - H2 phenomena (release, ignition, heat flux, overpressure)
  - Graphical User Interface (GUI) and generic assumptions
  - Flexible software architecture to enable improvements as science, data and models improve



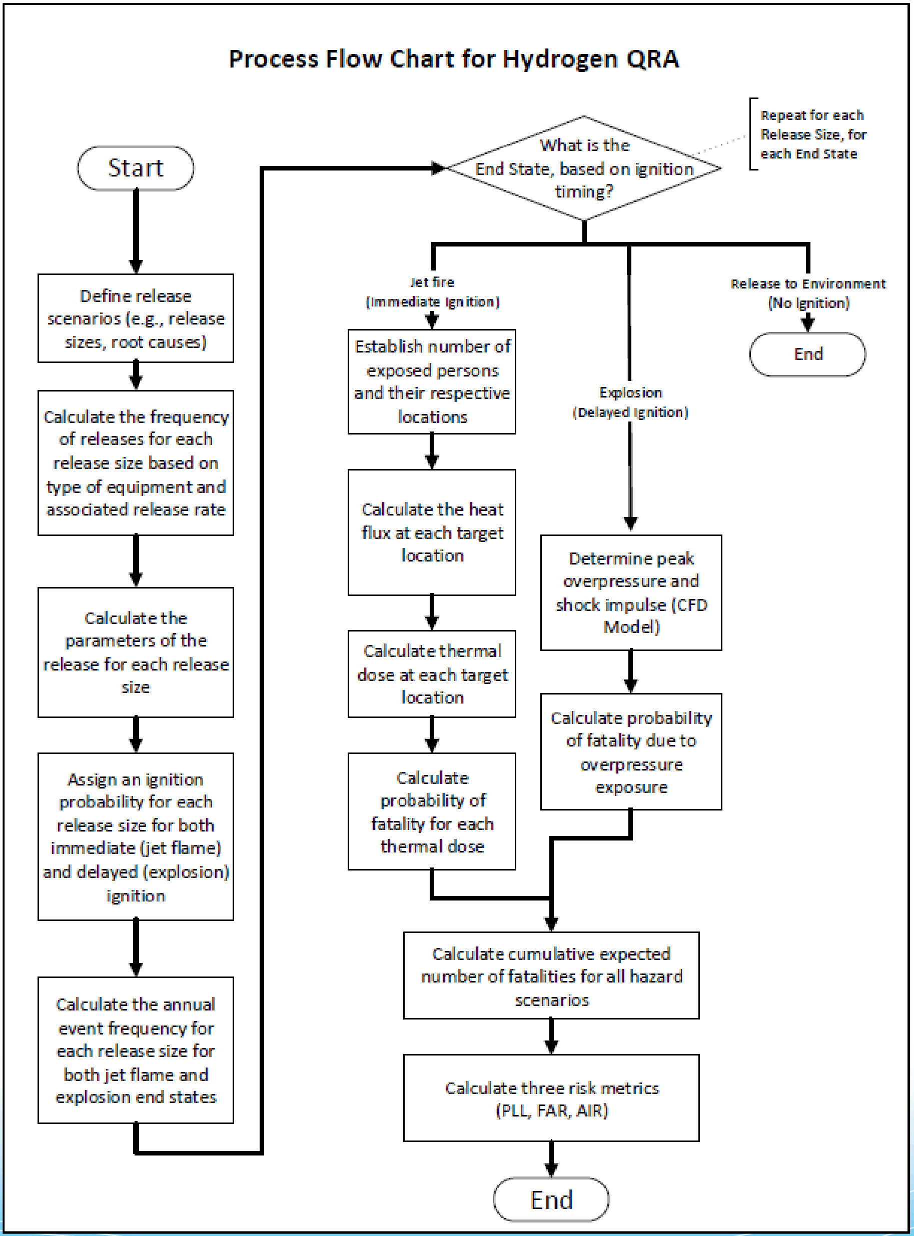
Risk assessment:
QRA Flow Chart

- Define the system
- Frequency/probability of the event(s) for the system
- Characterize the event(s)†
- Evaluate the consequence(s)†

Repeat as necessary

- Determine the cumulative risk exposure

† hydrogen behaviors



Risk Assessment: **HyRAM philosophy**

Framework of integrated tools to enable decision making

ISO TC197 WG 24 is developing international standard based on the principles encoded in HyRAM

1. Set analysis goals

2. System & hazard description

3. Cause analysis

4. Consequence analysis

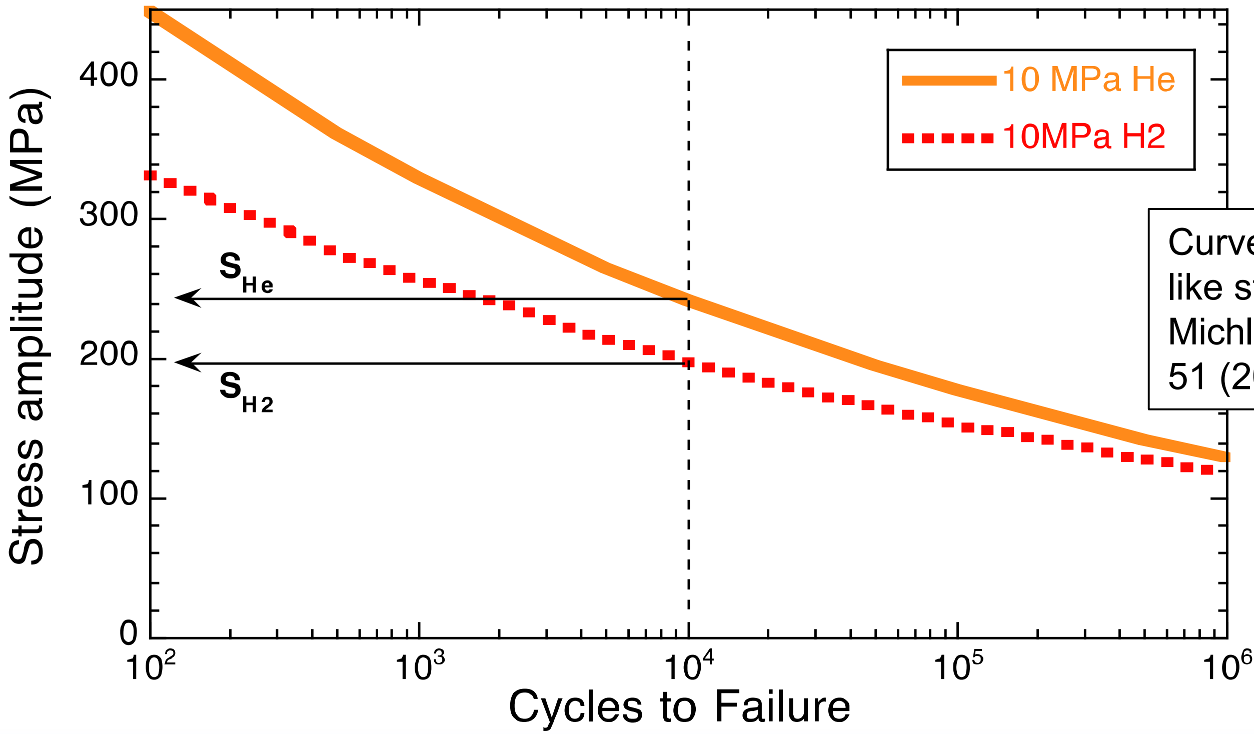
5. Communicate Results

User-specific – Each country/analyst can establish own analysis goals, defines own system

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

Materials compatibility: *Safety factor multiplier method* from CSA CHMC1

CSA CHMC1: Test methods for evaluating compatibility in compressed hydrogen applications

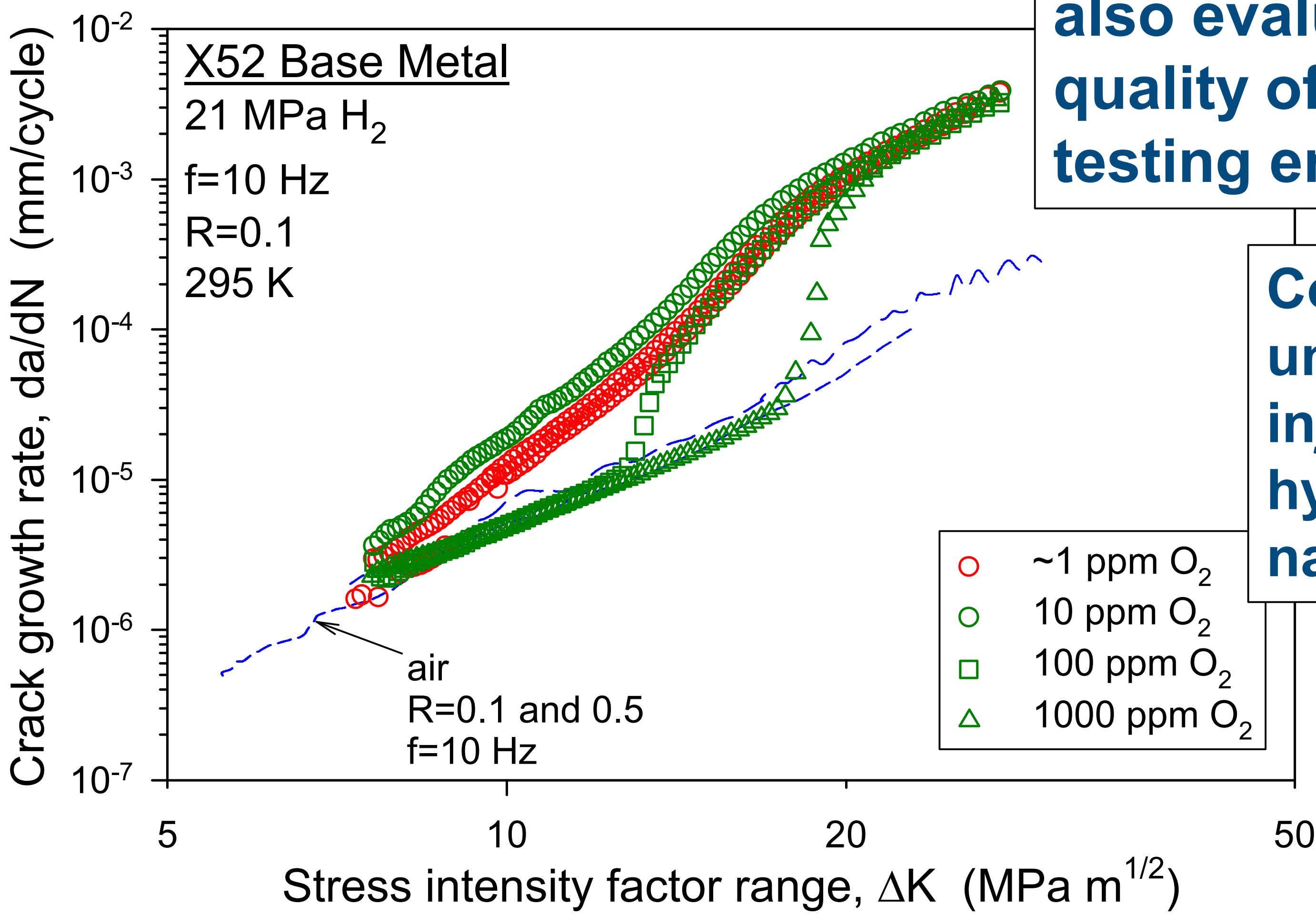


Curves based on data for 316-like stainless steel from: Michler et al., Intern J Fatigue 51 (2013) 1-7.

Safety factor multiplier is based on ratio of stress amplitude without and with hydrogen at a particular "life"

Materials compatibility:

Oxygen impurities can substantially affect fatigue in gaseous hydrogen

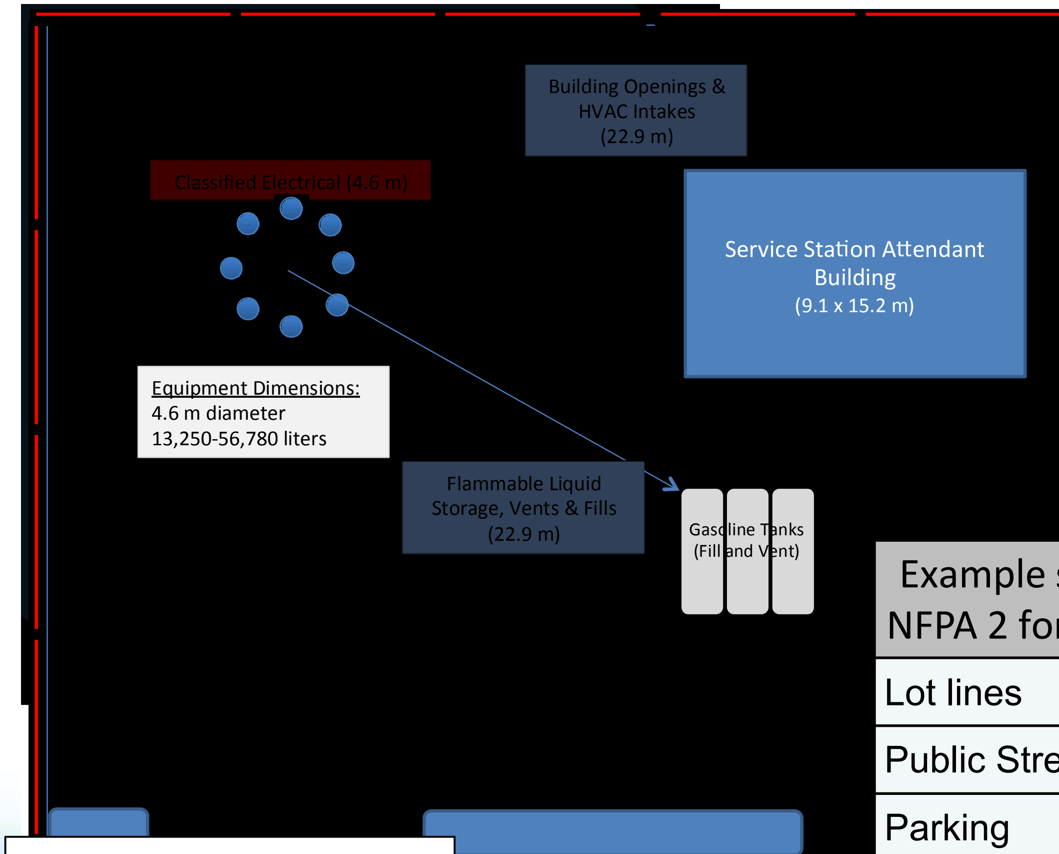


Test methods should also evaluate the quality of hydrogen testing environment

Concept key to understanding injection of hydrogen into natural gas

Future innovation: hydrogen behavior

Safety distances for liquid H2 storage are too large for commercial fueling stations in the US



LH2 storage

Goal: **use science-based approach to reduce safety distances for LH2**
- **NFPA activity**

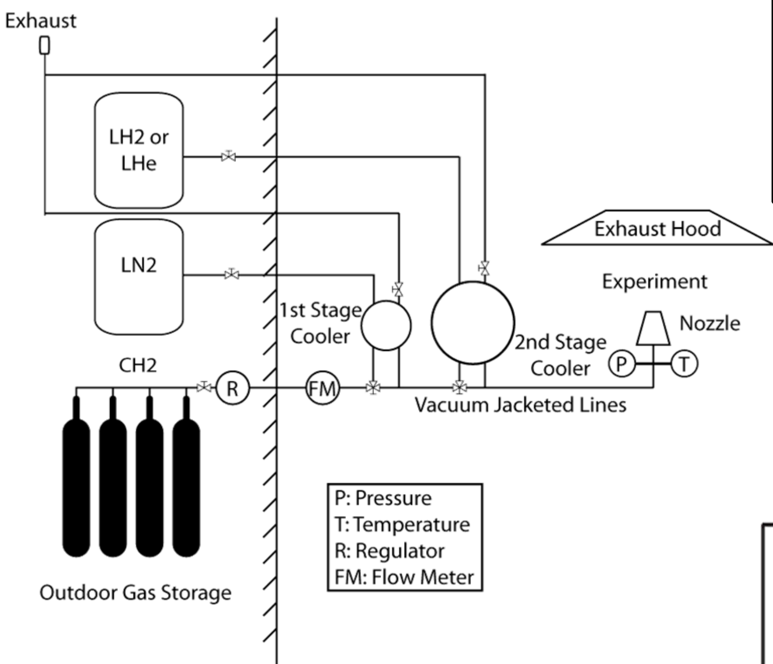
Harris et al. SAND2014-3416

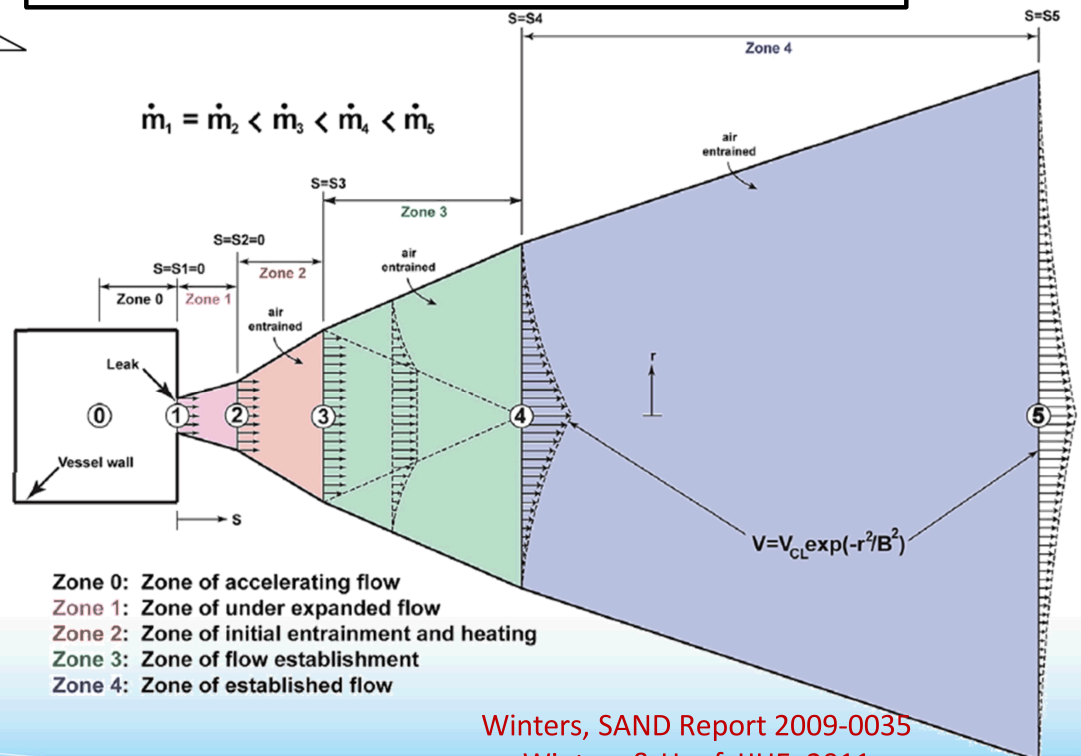
Example safety distances (m) NFPA 2 for specific boundaries	GH2	LH2
Lot lines	7.3	10.1
Public Streets, Alleys	7.3	10.1
Parking	4.0	22.9
Buildings (sprinkled, fire rated)	3.0	1.5
Building Openings or air intakes	7.3	22.9

Future innovation: hydrogen behavior

Development of laboratory capability to valid/update LH2 release models

New laboratory capability will accommodate release of hydrogen at temperature as low as ~20K





Existing cryogenic release model validated to 80 K

- **influence of humidity and air condensation?**

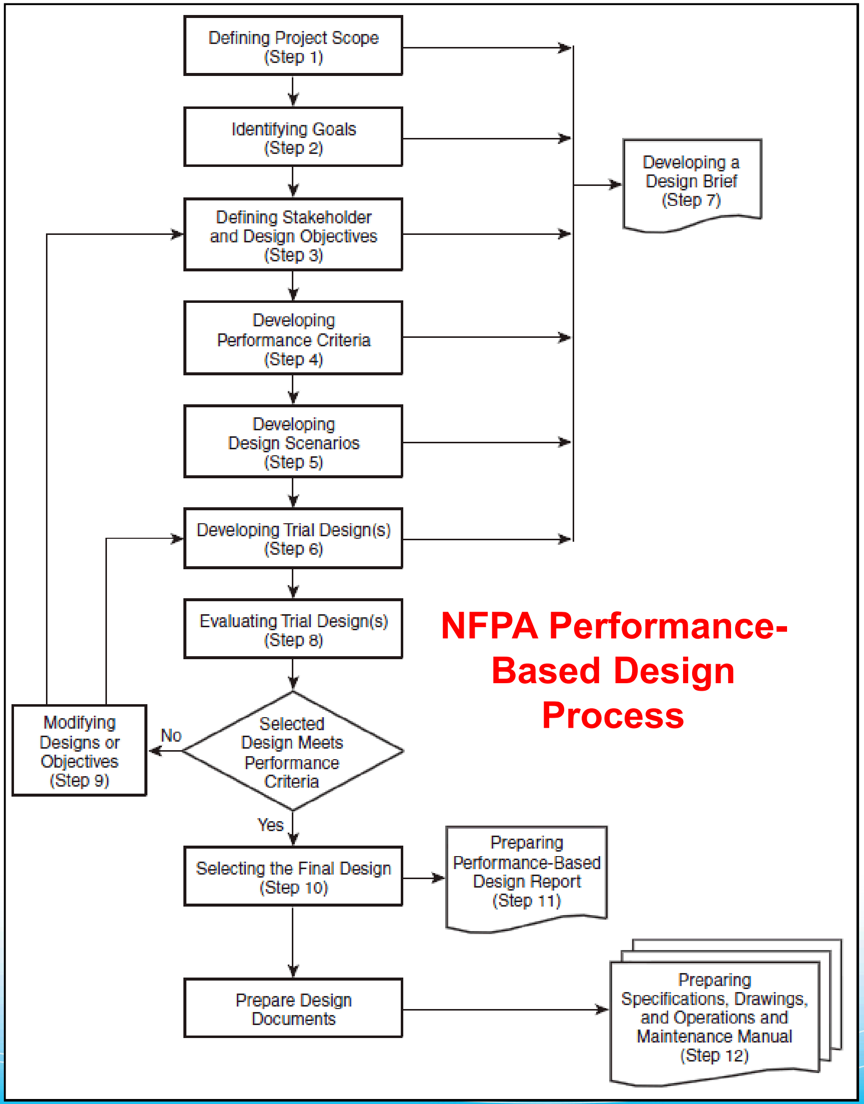
Winters, SAND Report 2009-0035
Winters & Houf, IJHE, 2011
Houf & Winters, IJHE, 2013

Future innovation: risk assessment

Performance-based system design (PBD) to establish relative risk profile

Goal: **establish methodology to perform performance-based assessment of risk**

- **Equivalent risk profile as prescriptive system**
- **Use quantifiable mitigations to relax requirements**
- **Makes use of hydrogen behavior models and HyRAM framework**



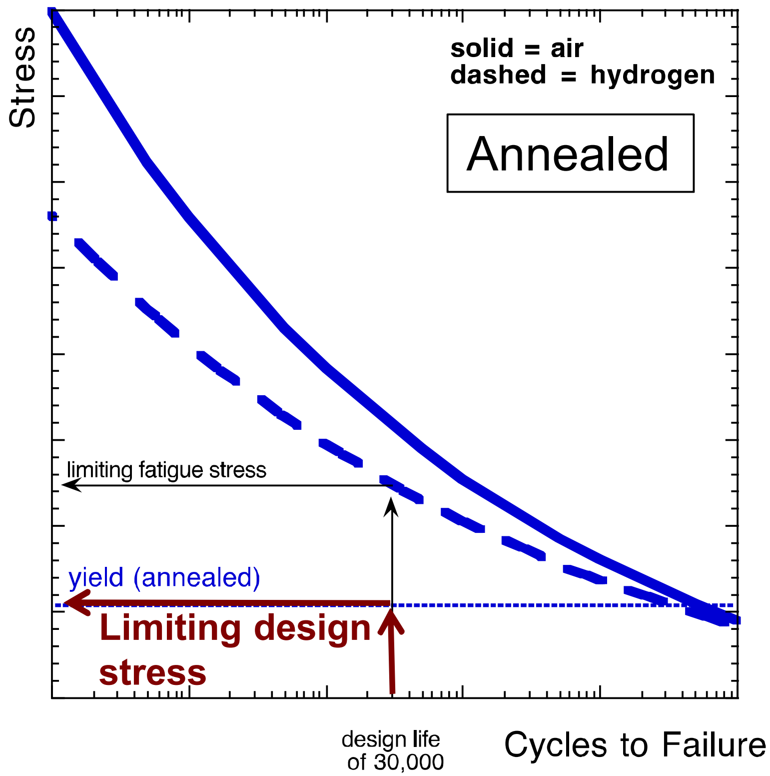
Future innovation: risk assessment
Add functionality to HyRAM

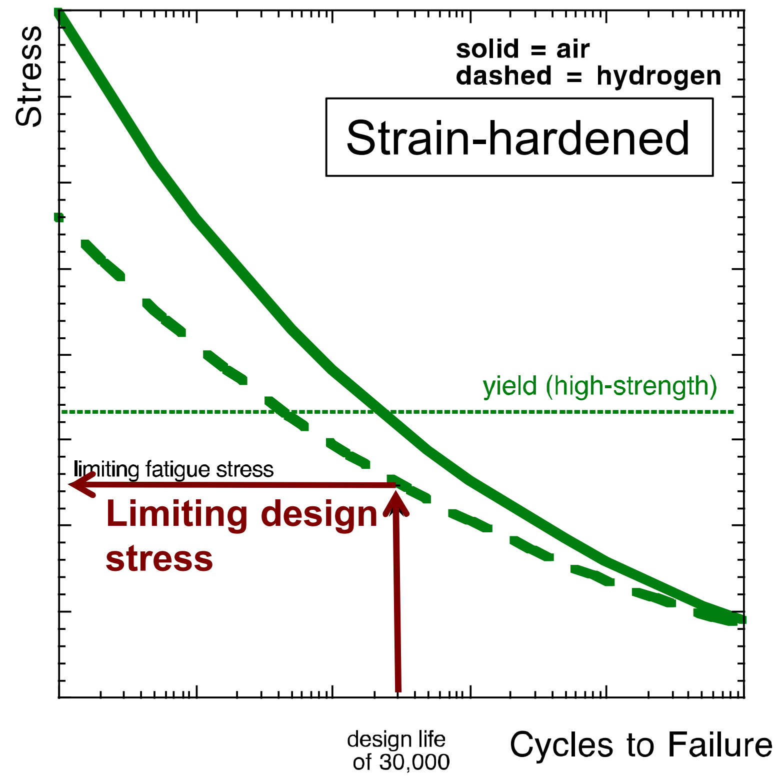
- **PBD template/structure for risk assessment**
- **Flexible fault tree and event tree analysis**
- **Risk importance measures** (e.g., contributions to risk)
- **Liquid plume model**
  - Unintended releases of LH2
  - Intended releases (e.g., to release head pressure after delivery)
- **Risk mitigations**
  - Quantify risk reduction due to barriers
  - Quantitatively account for other mitigations (sensors, flow restriction, etc)

HyRAM
HYDROGEN RISK ASSESSMENT MODELS

Future innovation: *materials compatibility*

Performance-based evaluation of materials provides quantitative rationale for materials selection



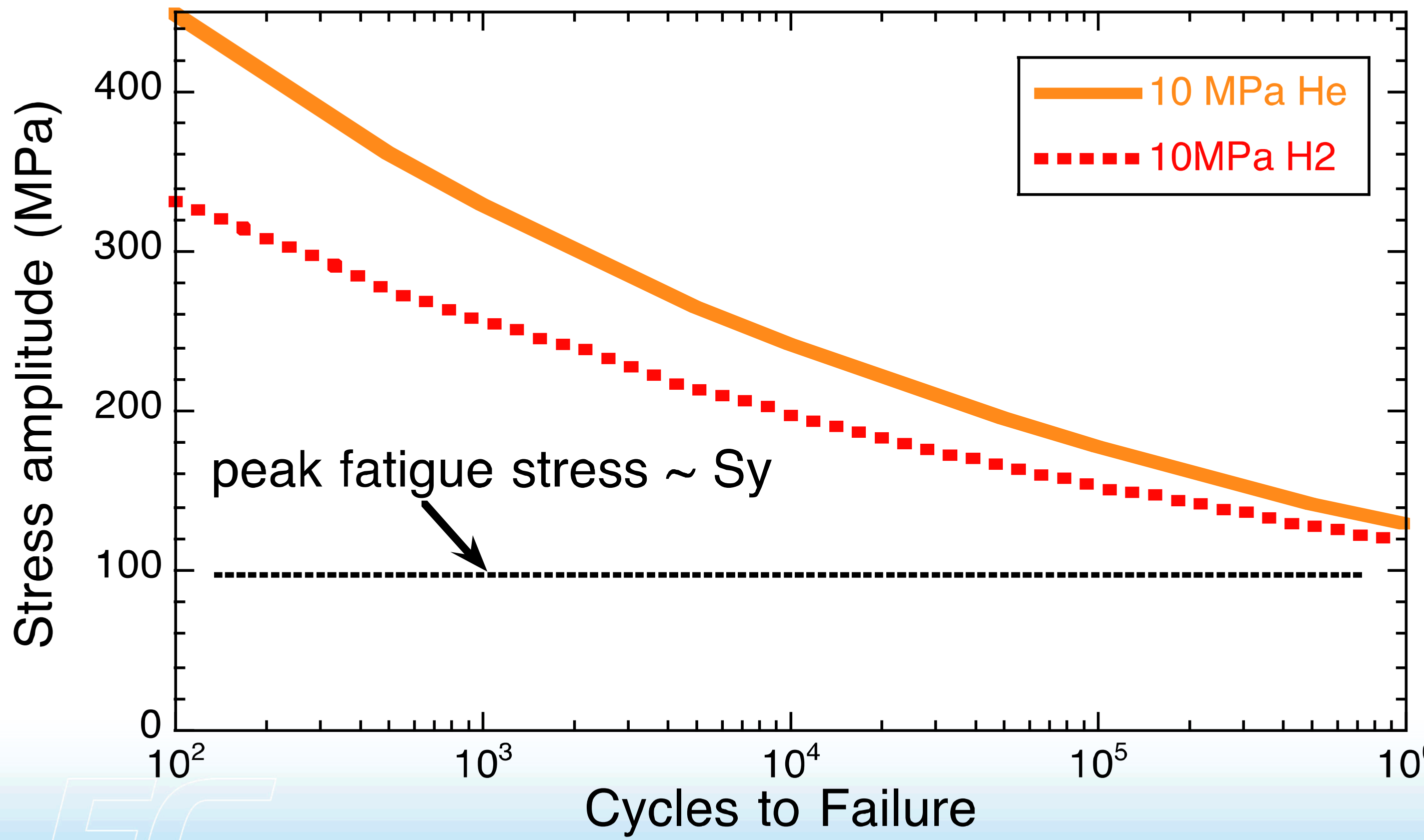


- Fatigue life strategy for hydrogen could be incorporated into prescriptive code (analogous to ASME BPVC VIII.3.KD-3)
- Enables the use of high-strength materials and optimized design

Summary

- *Hydrogen infrastructure and FCEVs are being deployed*
- *Research is a key component of enabling science-based approaches to codes and standards*
- *Active areas of R&D in hydrogen safety:*
  - **Hydrogen Behavior**
    - Physics-based models of high-pressure and cryogenic releases, as well as flame ignition/deflagration
  - **Risk Assessment**
    - Integration of consequences and causes into a quantitative risk framework: HyRAM
  - **Materials compatibility**
    - Test methods for performance-based selection of materials

Actual fatigue performance: Fatigue life is "infinite" for stresses less than the yield strength (i.e., for relevant design stresses)

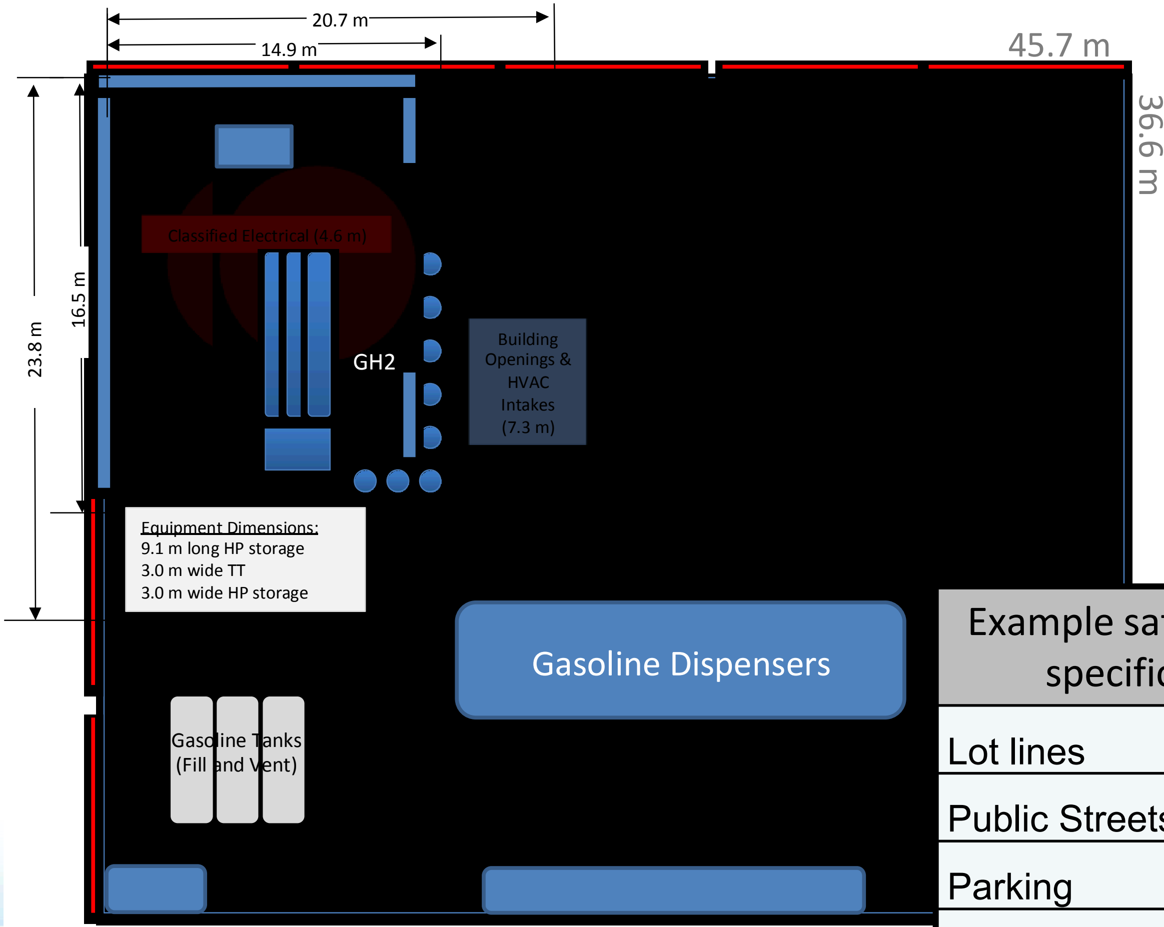


Curves based on data for 316-like stainless steel from: Michler et al., Intern J Fatigue 51 (2013) 1-7.

Major HyRAM needs from HySafe

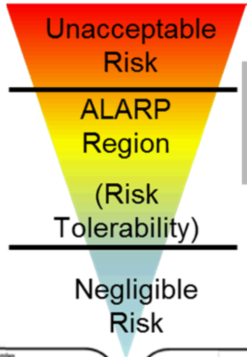
- **In one sentence: Models, data, validation and community engagement**
- Specifically:
  - Engagement with partners to refine QRA approach, standardize, review & adopt models (international and domestic, research and application)
  - Behavior models specifically developed & validated for application to hydrogen fuel cell problems
    - Developed as standalone C#, Python modules.
  - Lab-scale experiments, full-scale experiments, simulation for behavior models
  - H2 data for improving credibility of probabilistic event models (e.g., release frequencies, harm)
  - Validation activities to enhance credibility of behavior models and data originating from non-fuel-cell applications.

Hydrogen behavior:
Fire protection code uses safety distances informed by science

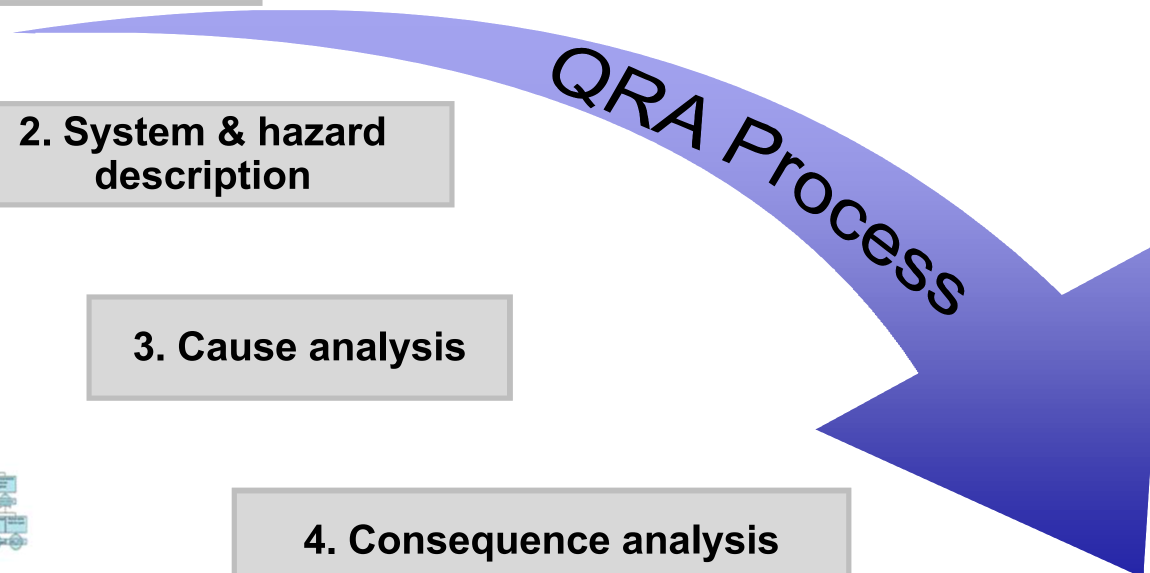


Example safety distances for specific boundaries	GH2	LH2
Lot lines	48	50
Public Streets, Alleys	48	50
Parking	25	n/a
Buildings (sprinkled, fire rated)	20	50
Building Openings or air intakes	48	75

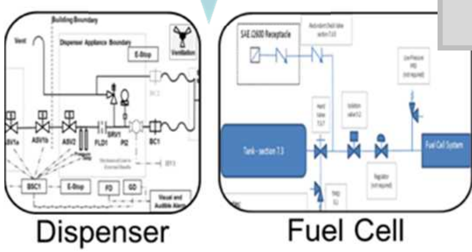
Risk assessment:
Integration of deterministic and probabilistic models



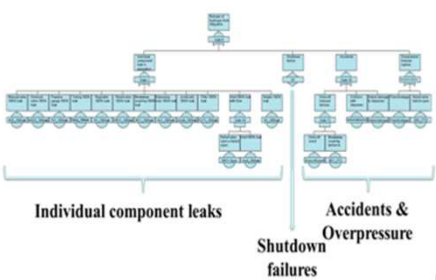
1. Set analysis goals



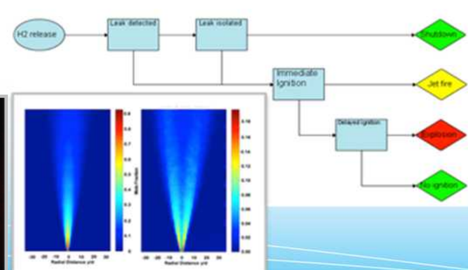
2. System & hazard description



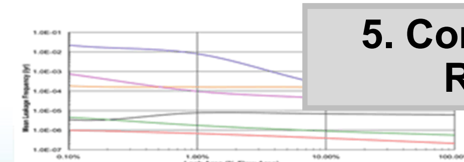
3. Cause analysis



4. Consequence analysis



5. Communicate Results

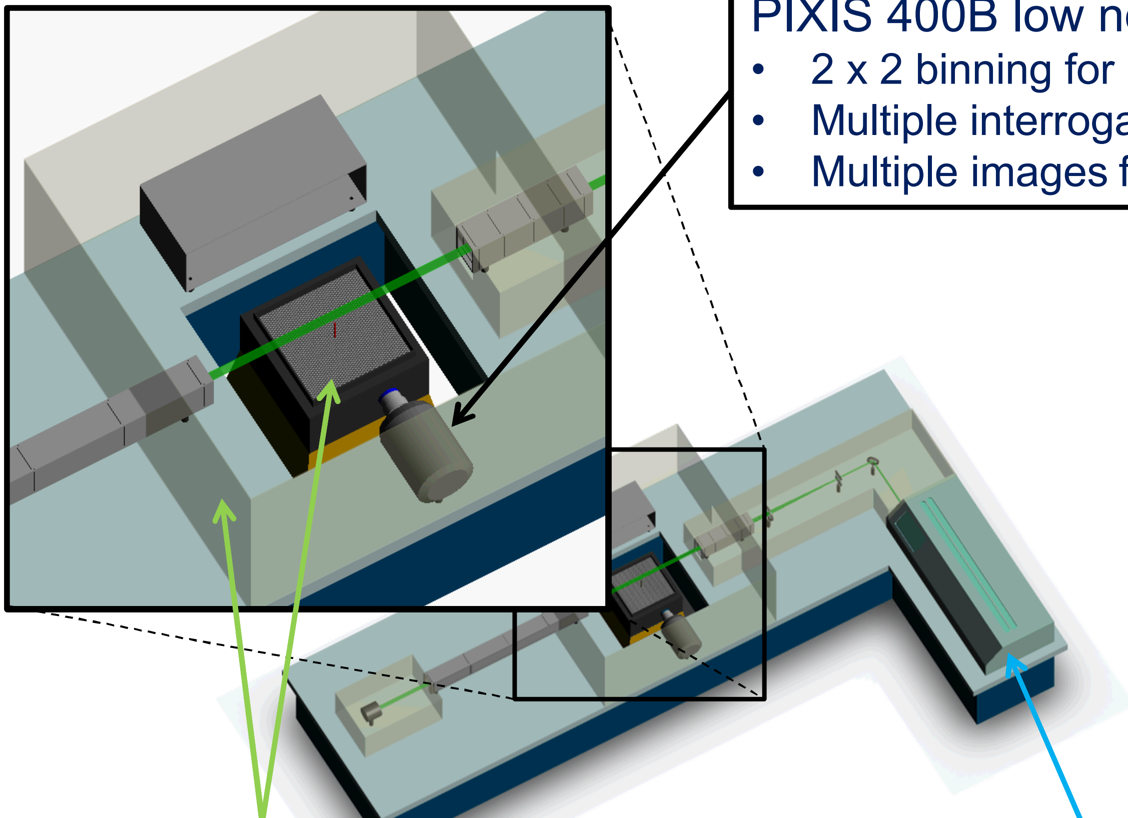


Occupation	FAR
U.S. Workforce total	1.8
Construction and extraction occupations	5.9
Industrial machinery, installation, repair, and maintenance workers	10.4
Industrial truck and tractor operators	3.0
Laborers and freight, stock, and material movers, hand	3.1
Farming, fishing, and forestry occupations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

Scalar field to be measured via Rayleigh scatter imaging in established flow zone to validate LH2 release model.

PIXIS 400B low noise CCD Camera

- 2 x 2 binning for high signal-to-noise (~400:1)
- Multiple interrogation regions to image full jet
- Multiple images for converged statistics



Air co-flow & barriers to minimize impact of room currents

Nd:YAG injection seeded laser (1 J/pulse @ 532 nm)

Opportunity for additional upstream measurements using complementary Raman diagnostics in an adjacent lab.

Modules in QRA toolkit (End-to-end or stand-alone)