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Application of Risk-Informed Approach to Hydrogen Codes and Standards

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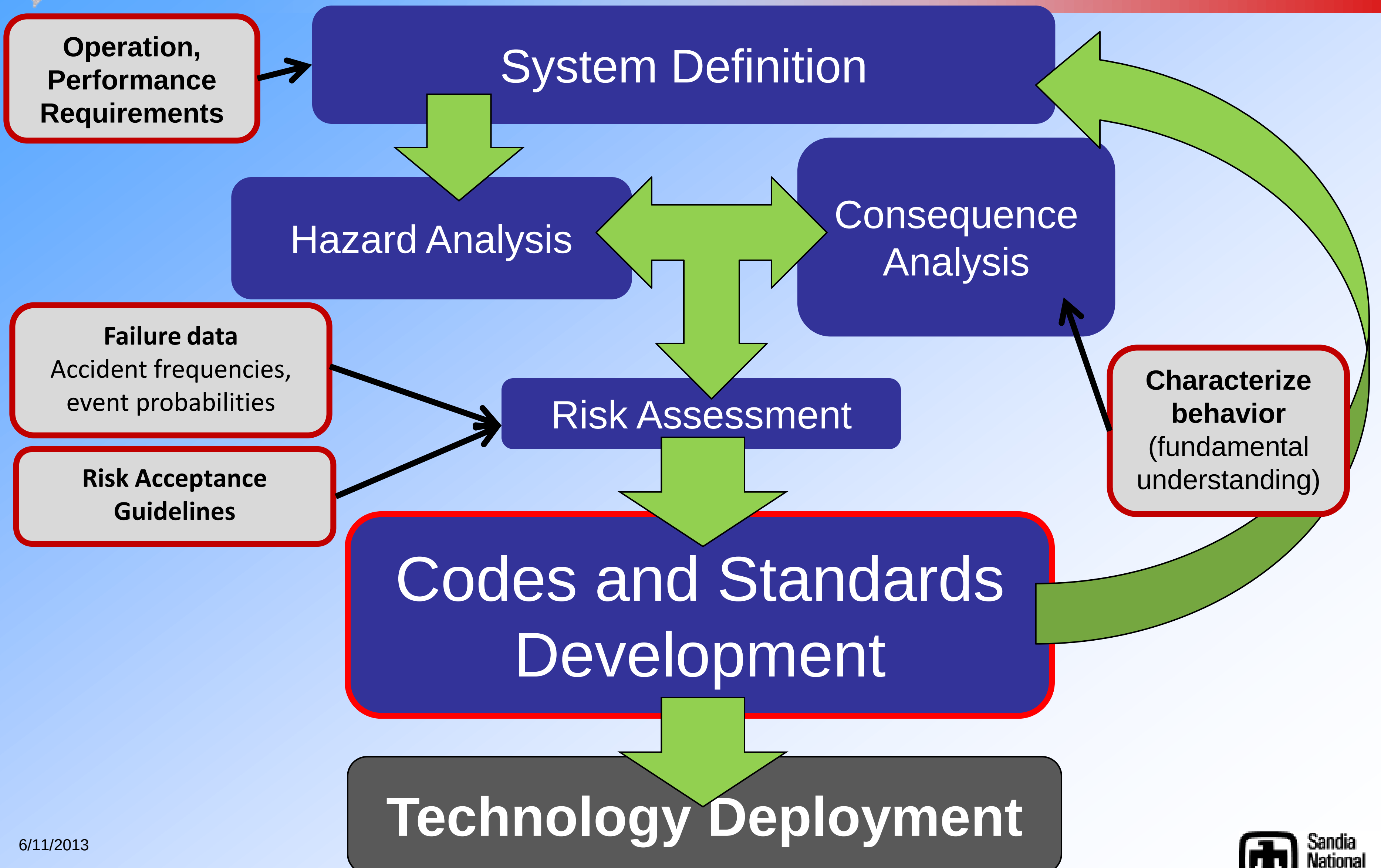
Risk-Informed C&S Process



Identify Analysis Goals and Methods

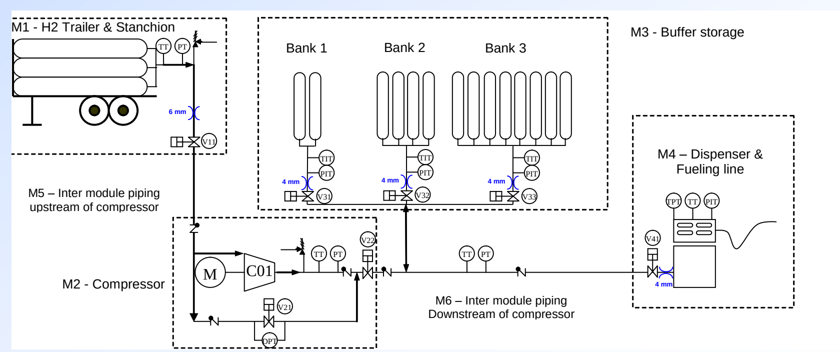
Not all C&S requirements have to be risk-informed!

- Goals:
  - Identify what requirements/features are to be evaluated in risk-informed approach.
  - Determine what kind of risks are being measured (fatalities? asset losses?) and what level of risk is acceptable.
  - Determine approach for doing the risk assessment.
  - Identify other considerations that will be involved in decision making.
- Method: Interaction with SDOs and other stakeholders.
- Output: A plan for conducting the QRA, which includes a defined goal, analysis targets, and risk criterion that are used to determine the acceptability of the final results.

Technical Accomplishments in Risk Assessment of Hydrogen Facilities

- Evaluation of risk-reduction potential of accident mitigation features
- Evaluation of risk associated with indoor refueling

- Establishment of risk-informed separation distances in NFPA and IFC standards for gaseous hydrogen facilities
- Expanded use and acceptance of QRA to establish risk-informed C&S requirements



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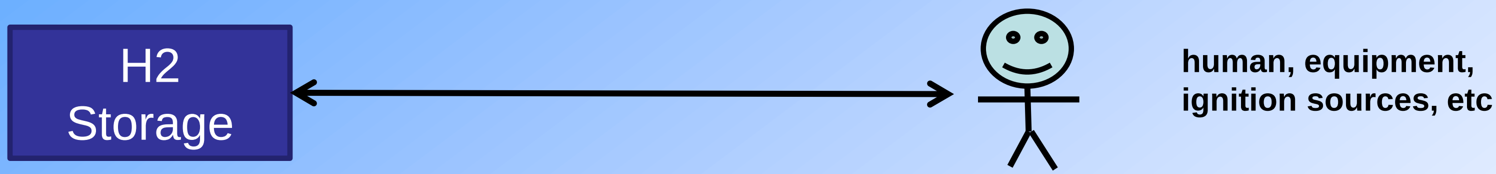
Risk-Informed

Separation Distances for Use in NFPA and IFC Hydrogen Codes and Standards

Separation Distances Define Spatial Location Requirements for a Facility

- Specified distances between a hazard source and a target



  - Basis for existing distances undocumented
  - Established distances do not reflect high pressures (70 MPa) being used in refueling stations

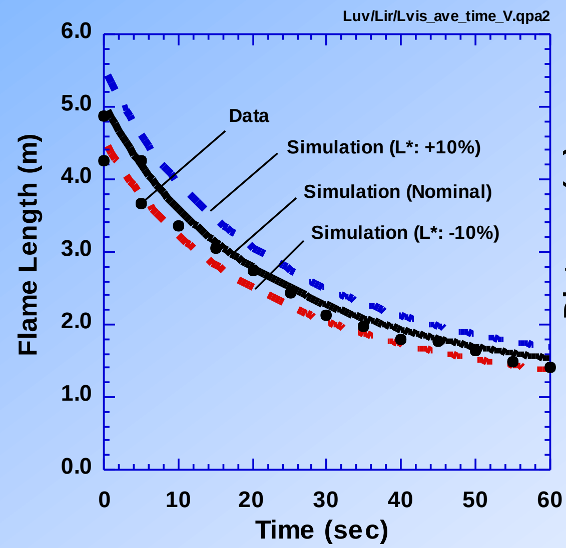
- Several options possible to help establish new separation distances
  - Subjective determination (expert judgment)
  - Deterministically, based on selected break size (e.g., 20% flow area)
  - Based only on risk evaluation as suggested by the European Industrial Gas Association (IGC Doc 75/07/E)

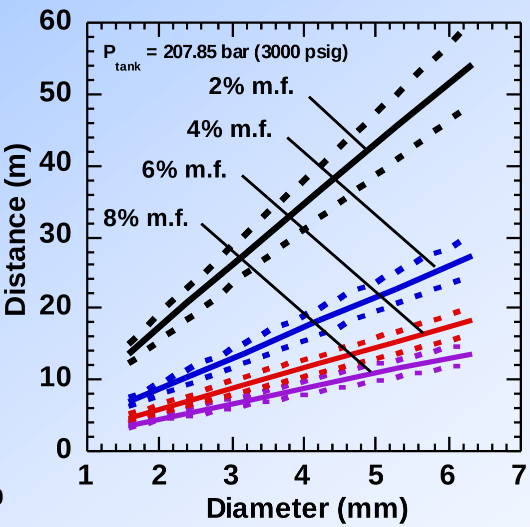
Risk-informed process combines risk information, deterministic analyses, and expert judgment

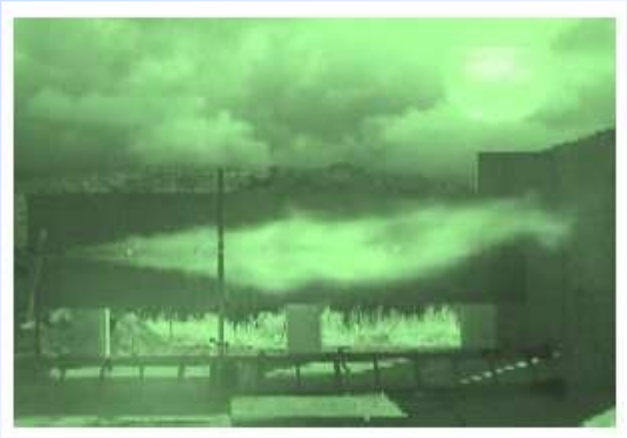
Appropriate and effective requirements

Sandia Hydrogen Leak Model

- Used to evaluate safety distances for hydrogen jets
- Model predicts (as function of system volume, pressure, and leak size):
  - Radiant heat flux from hydrogen jet flames
  - Visible flame length for ignited jets
  - Hydrogen concentrations in jets
- Assumes circular orifice for leak geometry and constant pressure - conservative
- Model validated against Sandia/SRI experiments

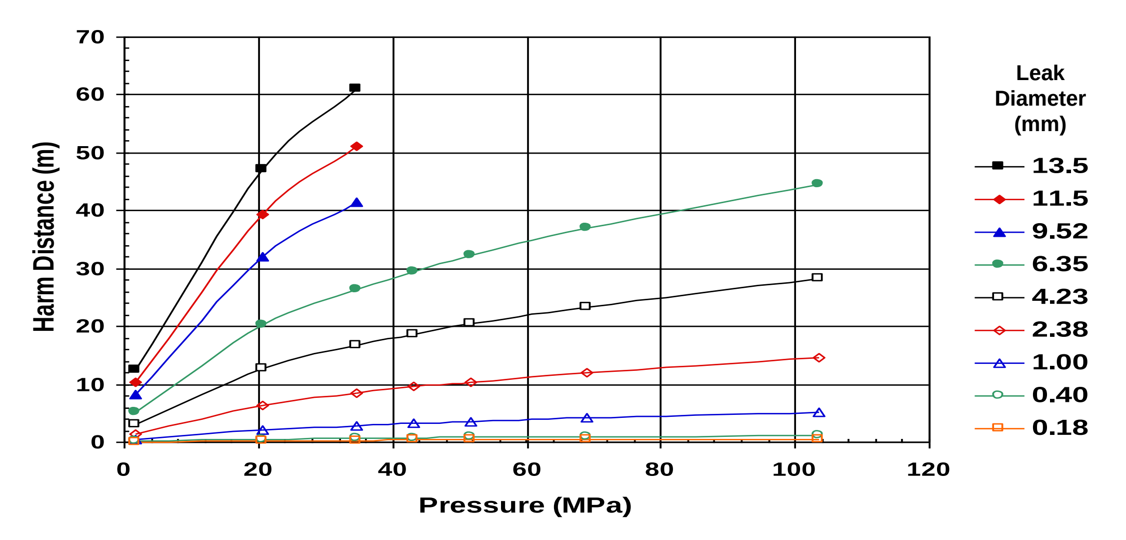


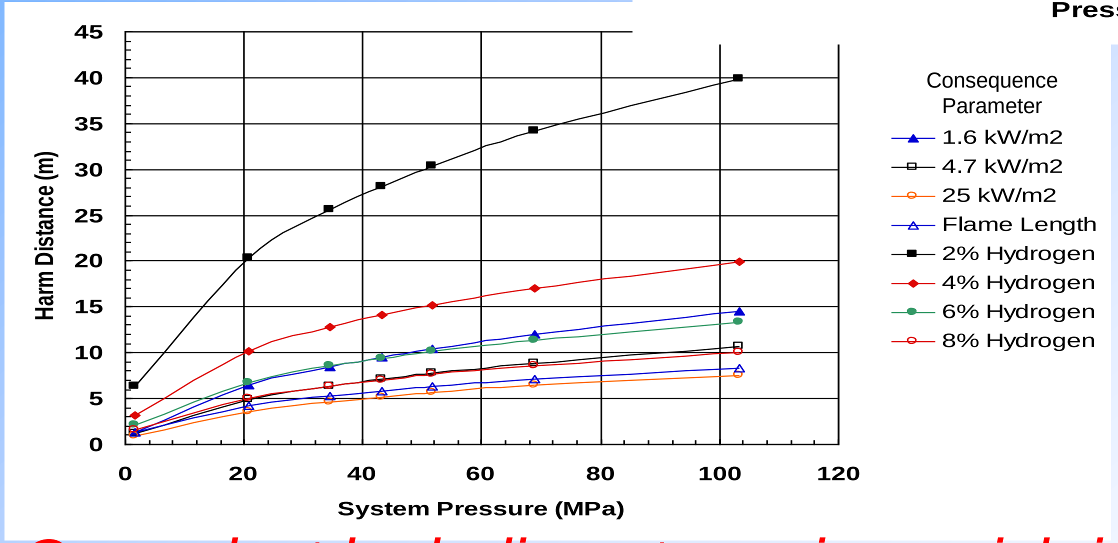




Deterministic-Based Separation Distances Vary Significantly with Leak Diameter

Hazard Distances for a Jet Fire – 1.6 kW/m^2 Radiation Heat Flux



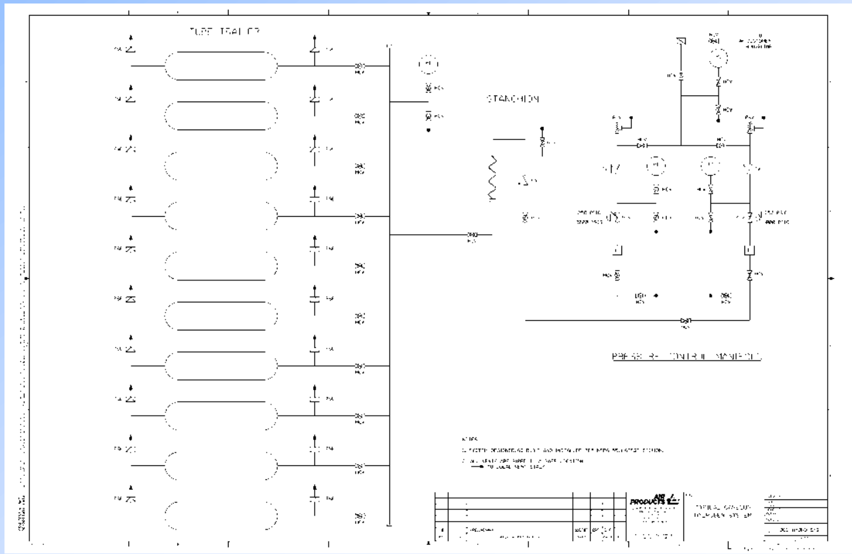


Hazard Distances for Different Consequence Measures – 2.38 mm Leak

Can select leak diameter using a risk-informed approach

Risk-Informed Approach to Select Leak Diameter

- Select typical gaseous storage systems as basis for evaluation
- Examine appropriate leakage data to determine leak size distribution
  - Selected leak size that encompasses 95% percent of leaks within the typical systems and could be expected during the lifetime of a facility



- Used QRA to determine if risk from leaks greater than selected leak size is acceptable for typical systems

Required Leakage Frequencies as a Function of Leak Size and Pressure

Very little hydrogen-specific data available:

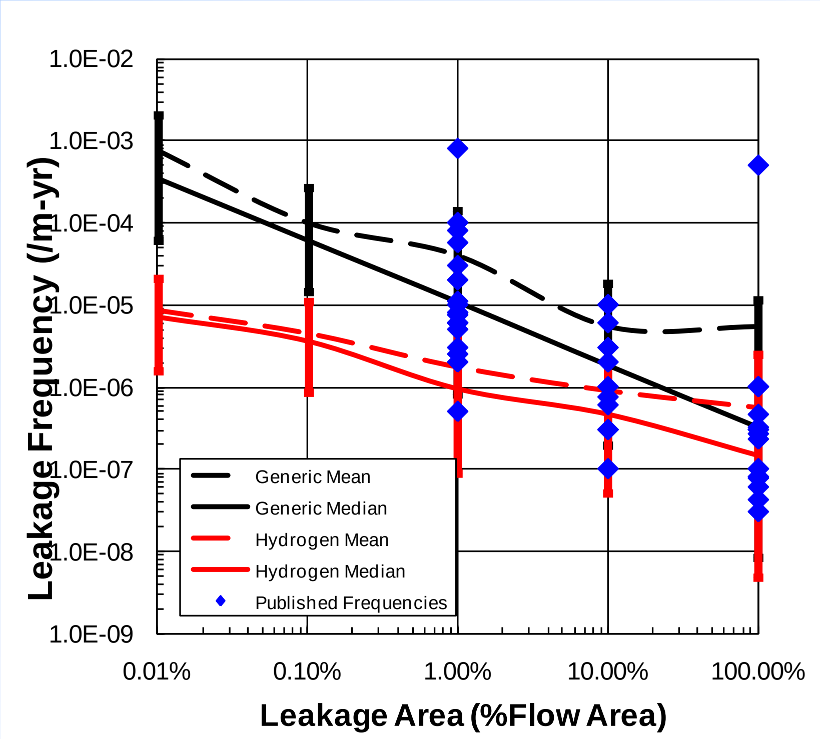
- Not enough for traditional statistical approach
- Instead, representative values are selected from other industries (oil and gas)

Problems with this approach:

- Not hydrogen specific
- Parameter uncertainty distribution is uncharacterized

Solution:

- Use Bayesian statistics to generate leakage frequencies
  - Combine sources of generic data with H_2 specific data
- Allows attachment of different “layers” of significance to the data



Reference: “Handbook of Parameter Estimation for Probabilistic Risk Assessment,” NUREG/CR-6823, U.S. Nuclear Regulatory Commission, Washington, D.C. (2003).

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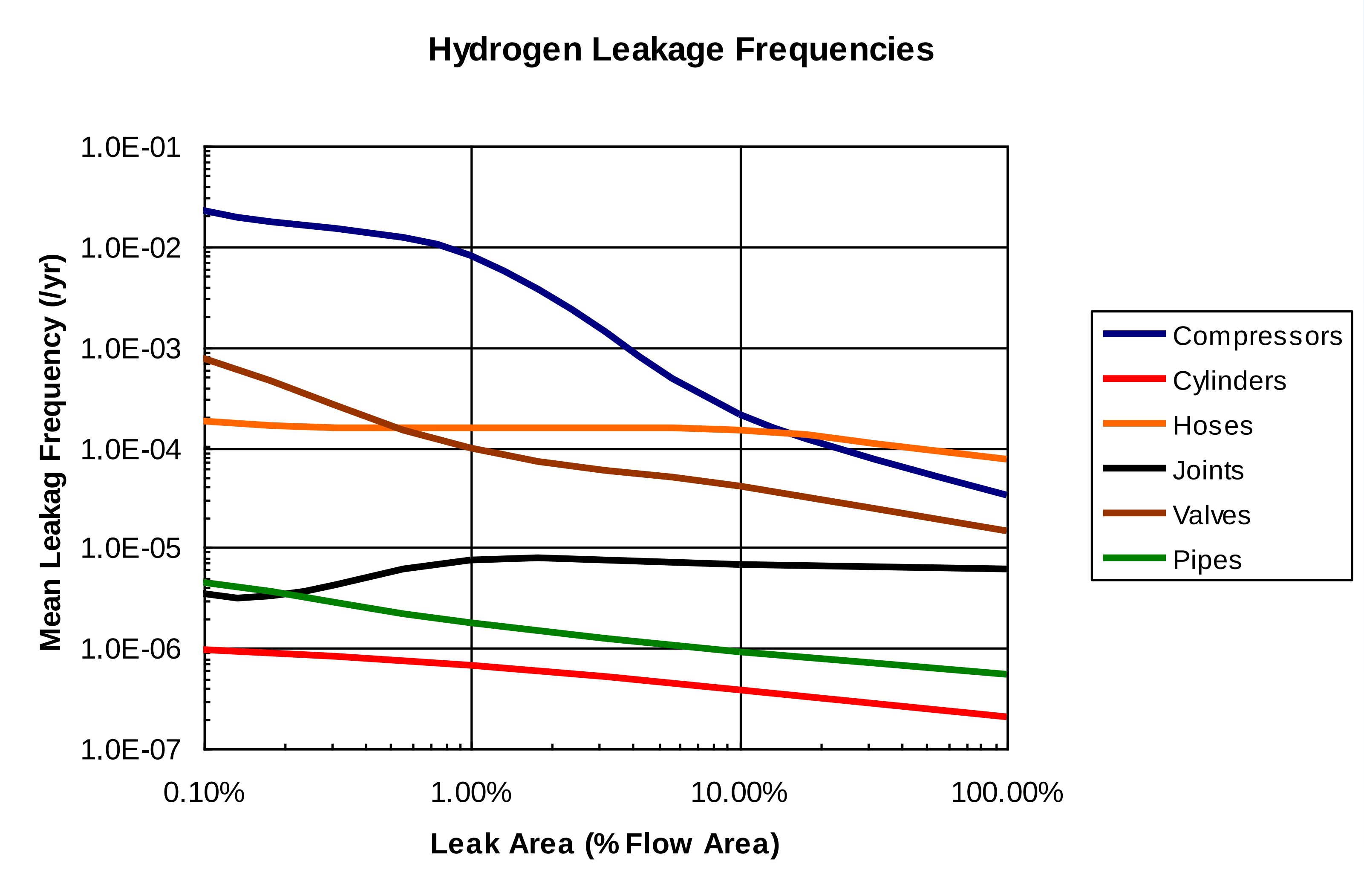
Mean Component Leakage Frequencies from Bayesian Analysis



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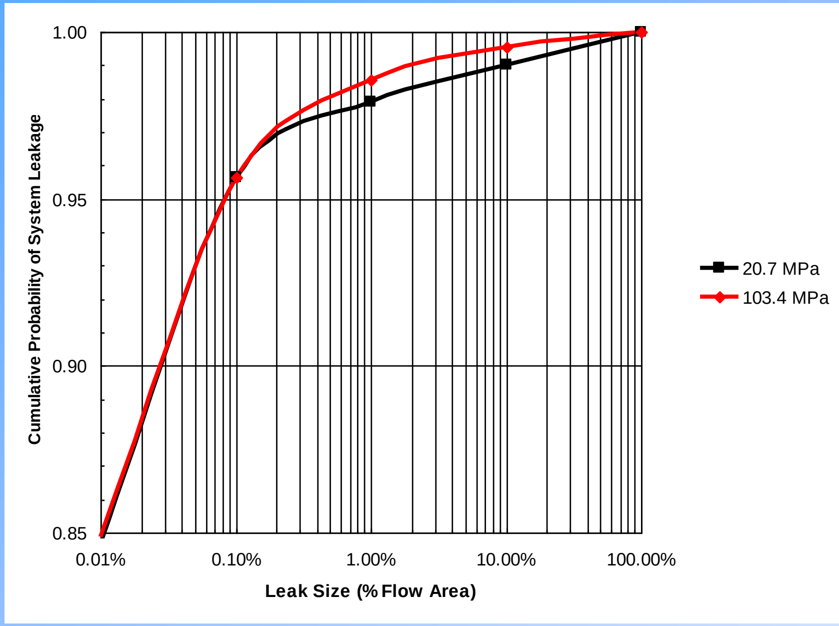
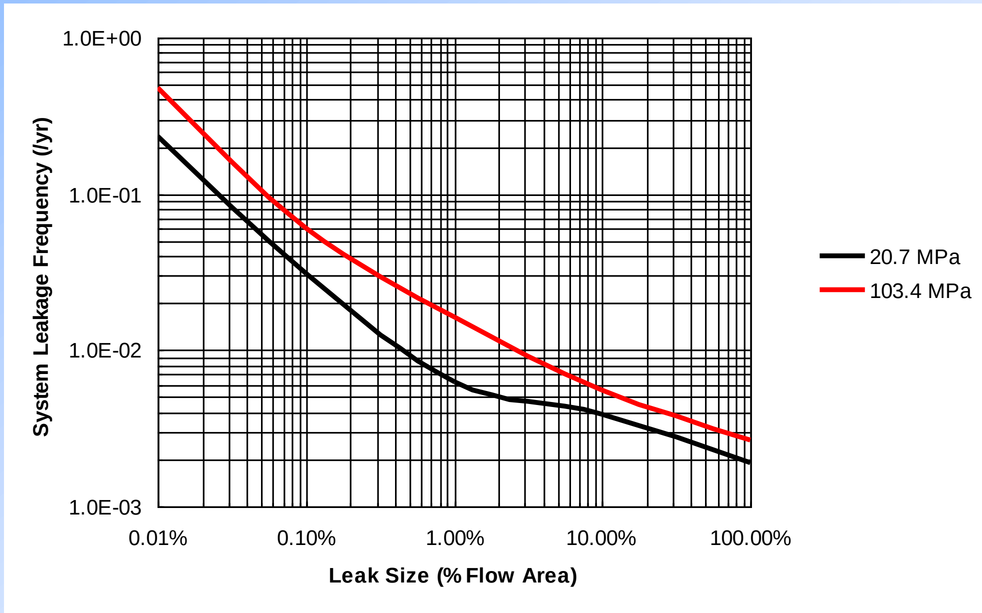
Component Leak Frequencies Used to Determine Cumulative System Leakage Probability

Evaluated for the representative storage facilities:





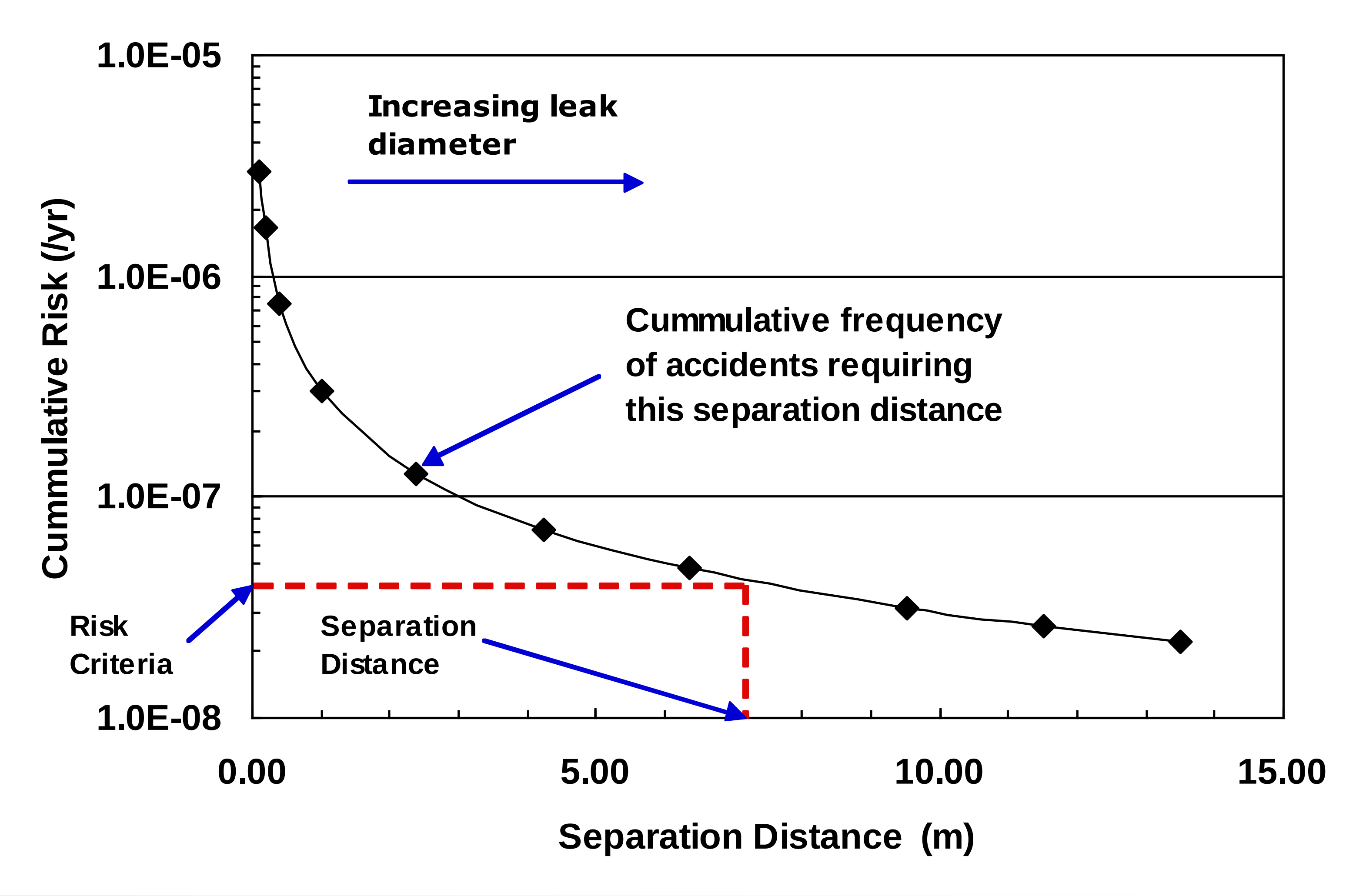
Expert opinion used to select 3% of system flow area:

- captures >95% percent of the leaks
- the resulting separation distances protect up to the 3% leak size
- QRA performed to determine if associated risk from leaks greater than this is acceptable

QRA Data, Models, and Assumptions

- Used leak frequencies from Bayesian analysis that incorporates hydrogen-specific data
- Used AVT ignition probabilities
- Person within 4% H_2 envelope or flame assumed to be a fatality
- Only includes random leakage events
- Risk from VCEs not included in analysis (high momentum jets)
- No volume effects have been incorporated (conservative)
- Surface effects not included (non-conservative)
- Assumes circular leaks (conservative)
- Accident propagation not included

Risk Approach for Establishing Adequacy of Safety Distances



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Selected Risk Guideline

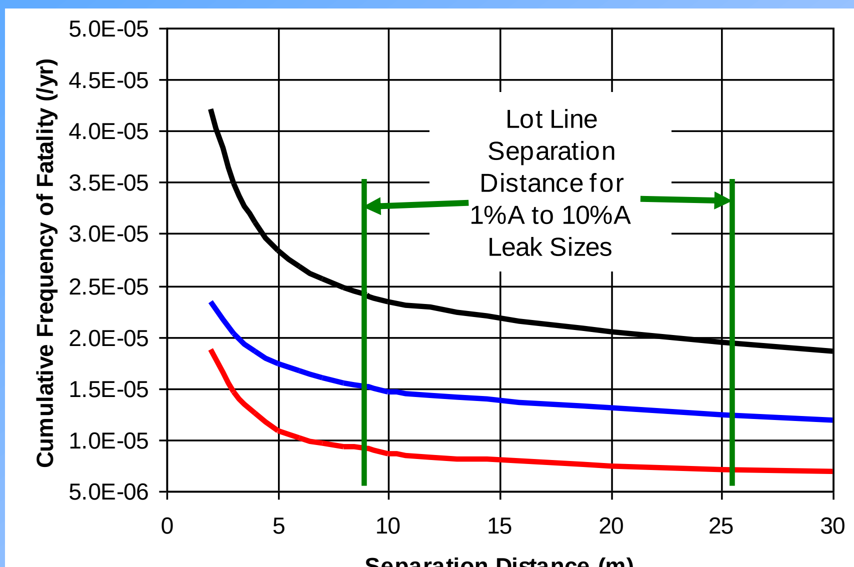
- Individual fatality risk to most exposed person at facility boundary selected for use in risk evaluation
- Use risk "Guideline" versus "Criteria"
  - Criteria varies for different countries and organizations
  - Making decisions based on comparison to hard risk criteria difficult because of uncertainties in risk evaluations
    - Comparison of mean risk to guideline is usually done
    - Sensitivity studies and uncertainty analysis used to determine importance of assumptions

NFPA 2 Working Group chose 2E-5 fatalities/yr as guideline

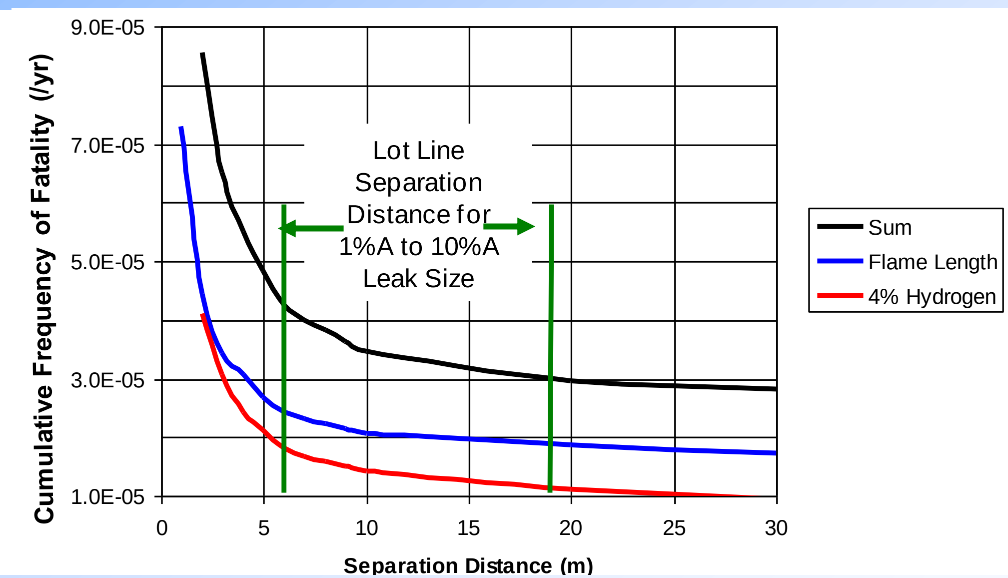
Basis – Comparative risk to gasoline stations, 10% of risk to society from all other accidents, 1E-5/yr is a value used by most countries that have established a risk criteria

Risk Results for Representative Systems

Total Risk 20.7 MPa (3000 psig) System



Total Risk 103.4 MPa (15000 psig) System



J. LaChance et al., "Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards", SANDIA REPORT, SAND2009-0874, Printed March 2009

- Risk close to the "guideline" of 2E-5 fatalities/yr selected by NFPA Task Group 6
- Risk from leaks greater than 3% of flow area were deemed acceptable

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This Effort Validated the Risk-Informed Approach for Establishing Requirements

- NFPA 55 voted to accept the new hydrogen bulk storage separation distances table
  - New table approved for NFPA 55 and 52 (available in 2010 editions)
  - New table included in NFPA 2
  - HIPOC supported inclusion in IFC by referencing back to the new table in NFPA 55 (available in 2010 edition of IFC).

This effort provided a model for additional codes and standards development efforts:

- *Requirements related to mitigation features (e.g., barriers)*
- *Requirements related to indoor refuelling*

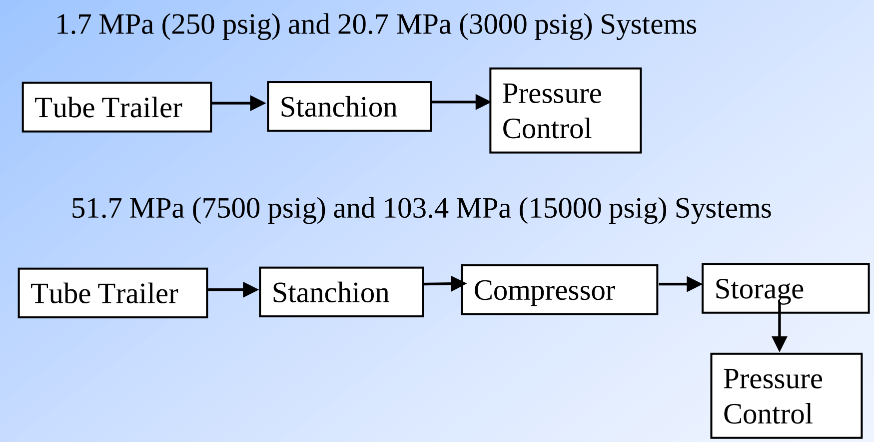
Risk Reduction Potential of Accident Mitigation Features

Accident Mitigation Features Can Be Used to Reduce Risk and Separation Distances

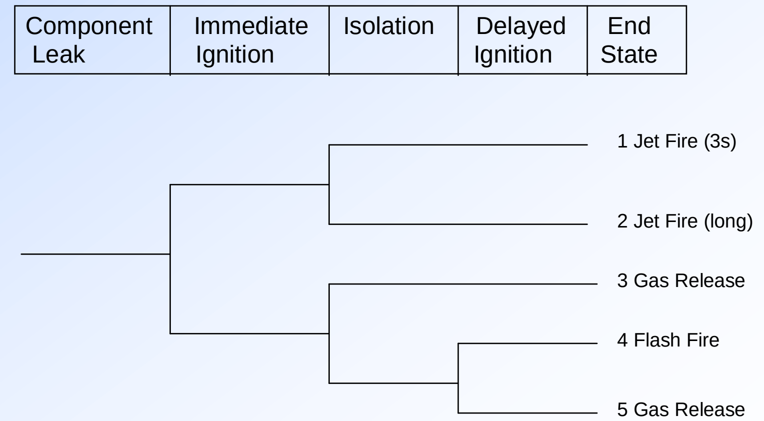
Risk-reduction potential evaluated for the following features:

- Active Detection and Isolation
  - Exterior detectors (hydrogen and flame)
  - Process flow detection (pressure and flow)
  - Excess flow valves
- Flow Limiting Orifices
- Reduction in Number of Components (leak reduction feature)
- Barriers

Example facilities used in evaluation



Accident sequence model



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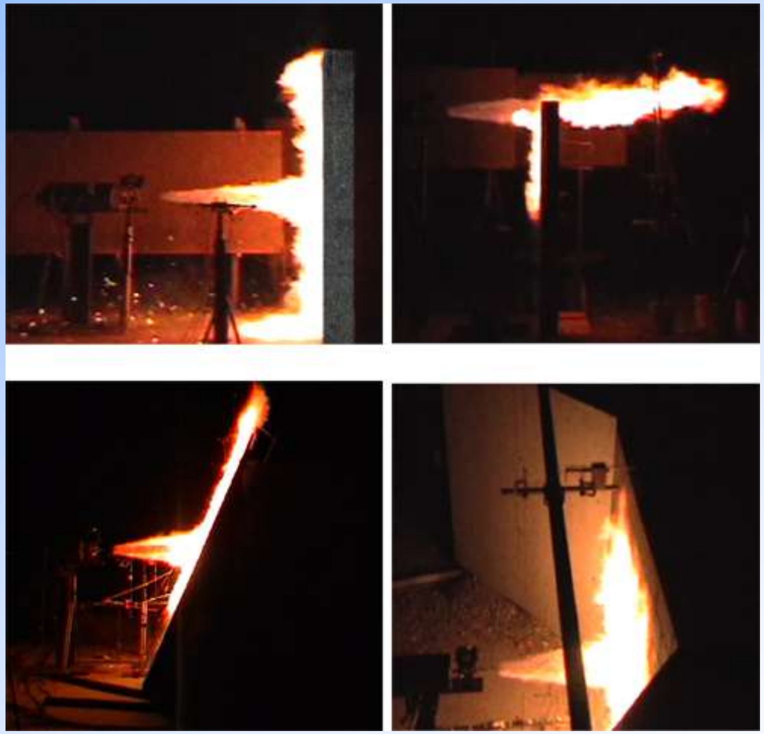
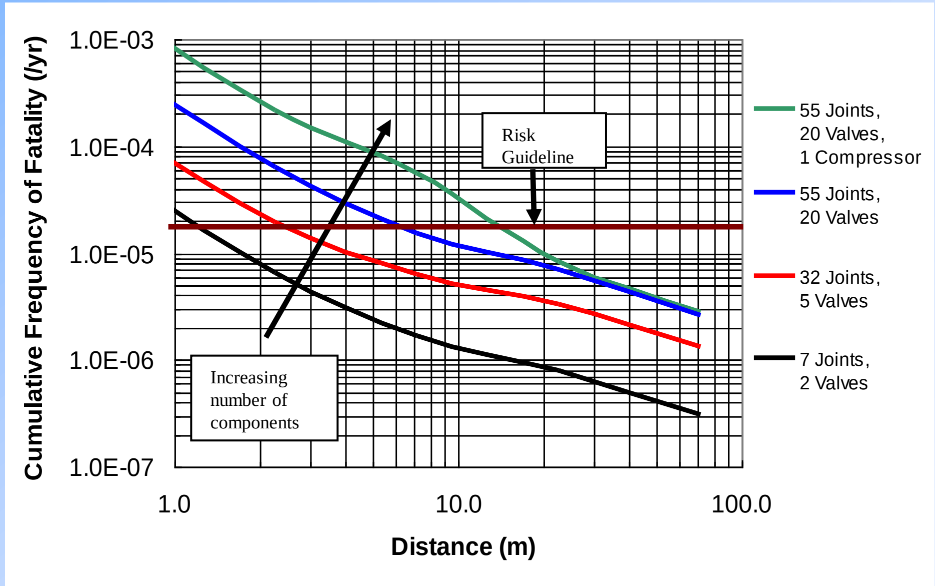
Mitigation Features Can Reduce the Frequency and Consequences of Accidents

Barrier walls will reduce the consequences from hydrogen jets if properly configured:

- Reduces unignited jet flammability envelope
- Deflects jet flames and protects from direct flame impingement
- Reduces thermal radiation exposure
- Does not introduce significant overpressure hazards





Reducing the number of high risk components (joints, valves, compressors, and hoses) in a system is effective in reducing the frequency of leaks and corresponding risk

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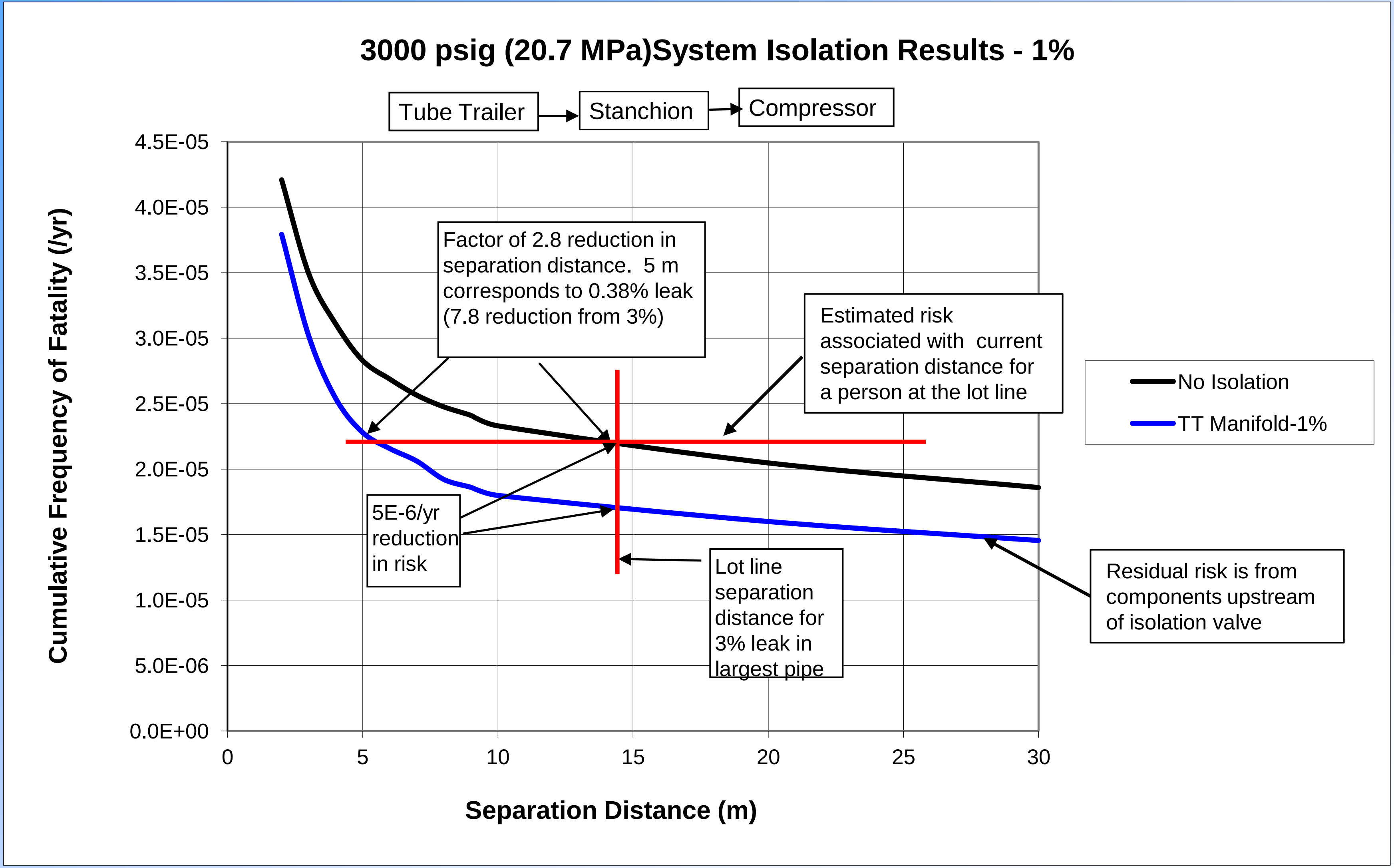
Detection and Isolation

- Assumed 1% flow area leaks can be detected and isolated with 0.9 reliability
  - Sensitivity performed if 10% leaks are detected

Isolation Valve Location	
3000 psig (20.7 MPa) System	**15000 psig (103.4 MPa) System**
Tube trailer manifold	Tube trailer and high pressure storage manifold
	Tube trailer manifold
	High pressure storage manifold
Outlet of stanchion	Outlet of stanchion
On tube trailer cylinders	Tube trailer manifold and high pressure storage cylinders

Example Risk Reduction – Detection/Isolation



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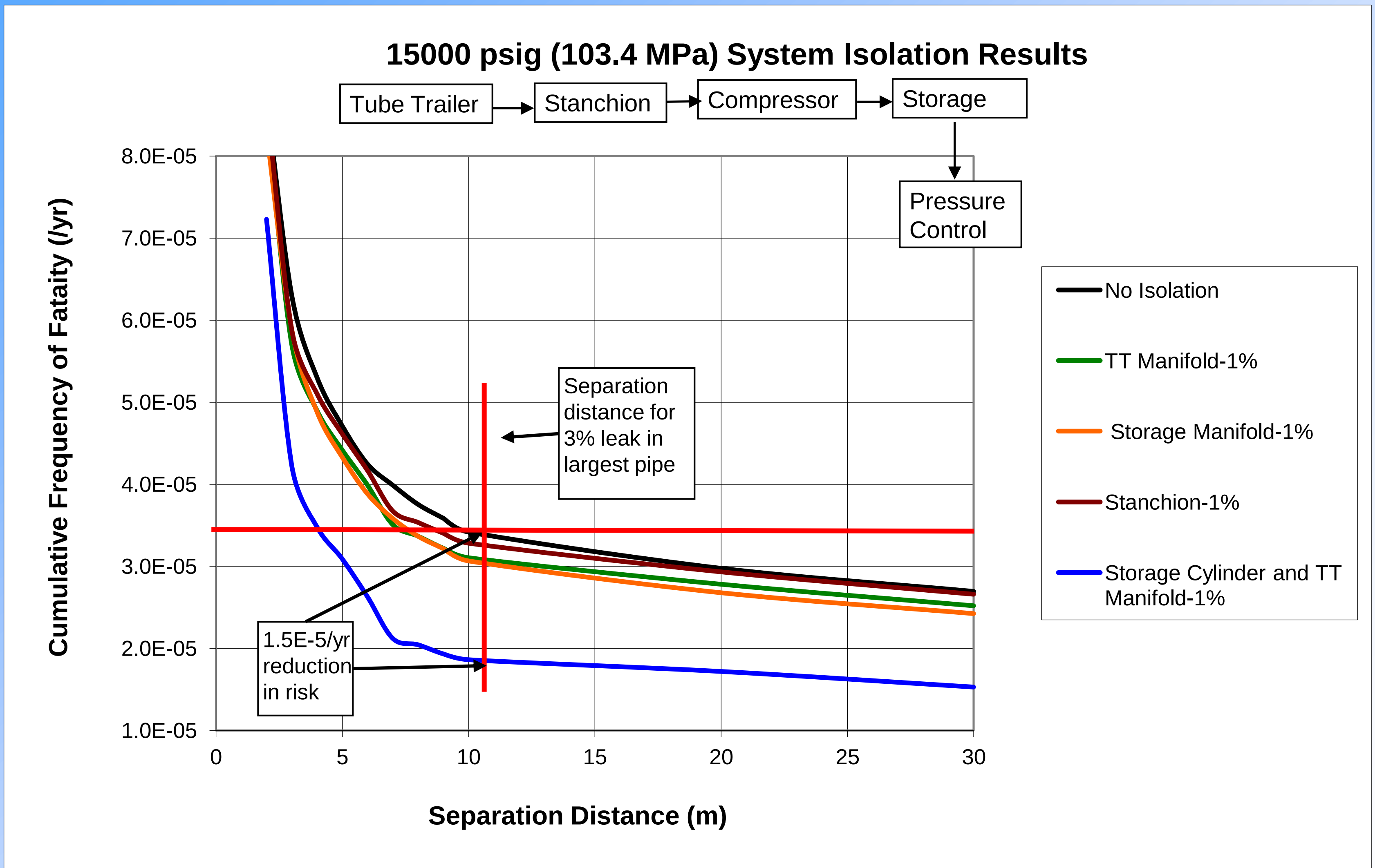
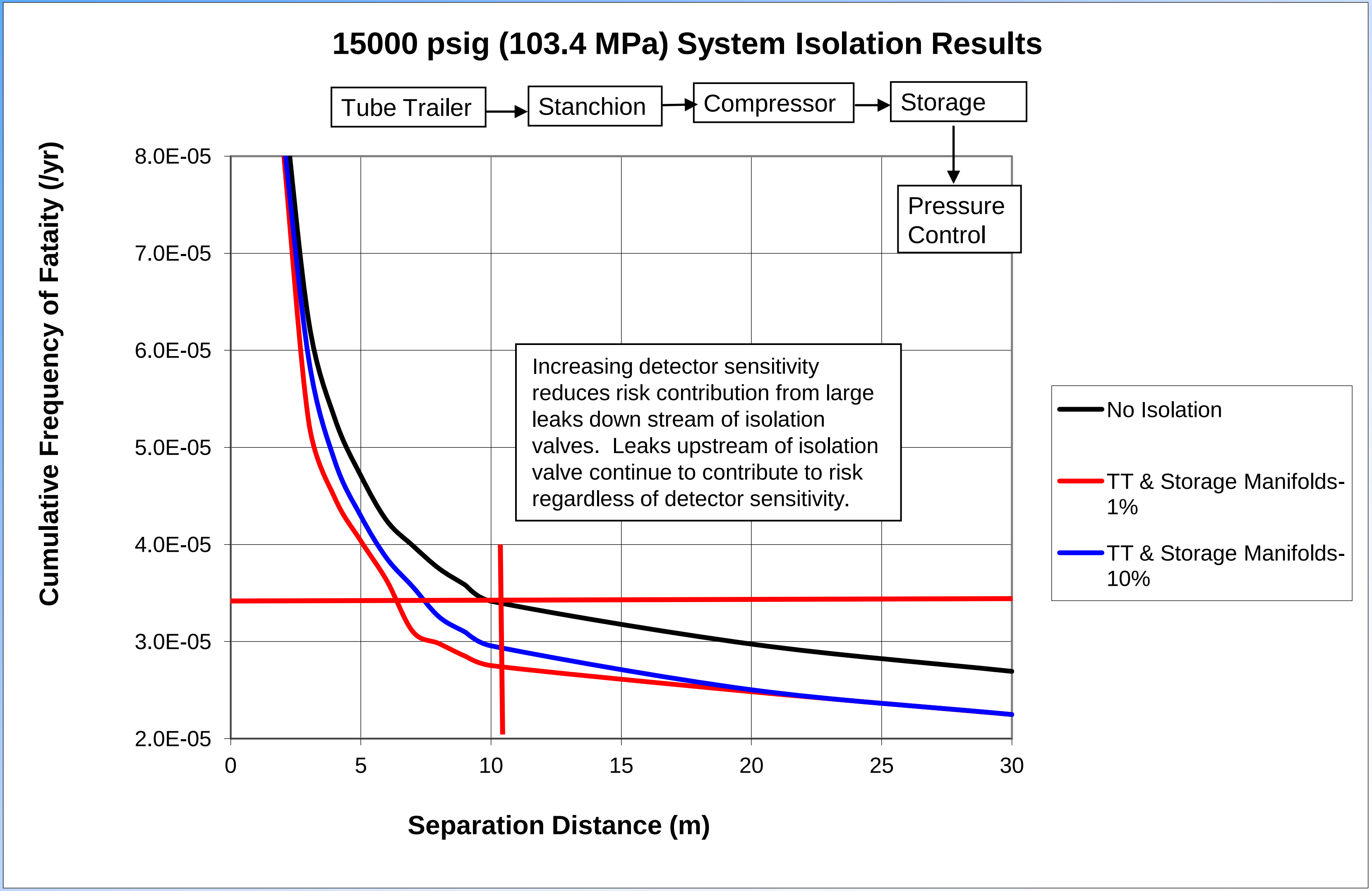
Isolation Valve Location Sensitivity



Detection Sensitivity



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Mitigation Feature Summary

- Mitigation features can be used to reduce the risk or separation distances at hydrogen facilities
  - Effectiveness of leak detection and isolation system is dependent upon detection capability and isolation location
  - Flow limiting orifices, if process allows, can limit maximum leak size down stream of orifice
  - Reducing the number of risk-significant components (e.g., joints and valves) in a system reduces the leak potential
  - Barriers are effective in reducing the consequences from hydrogen releases

Indoor Refueling of Forklifts

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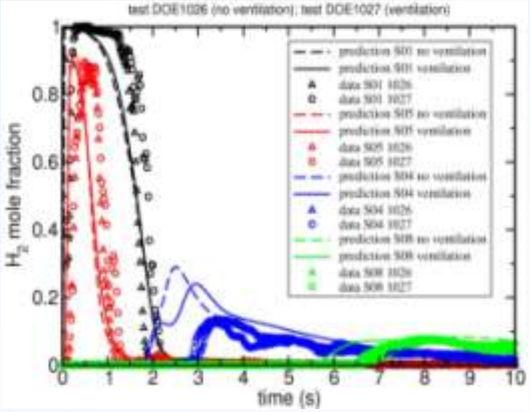
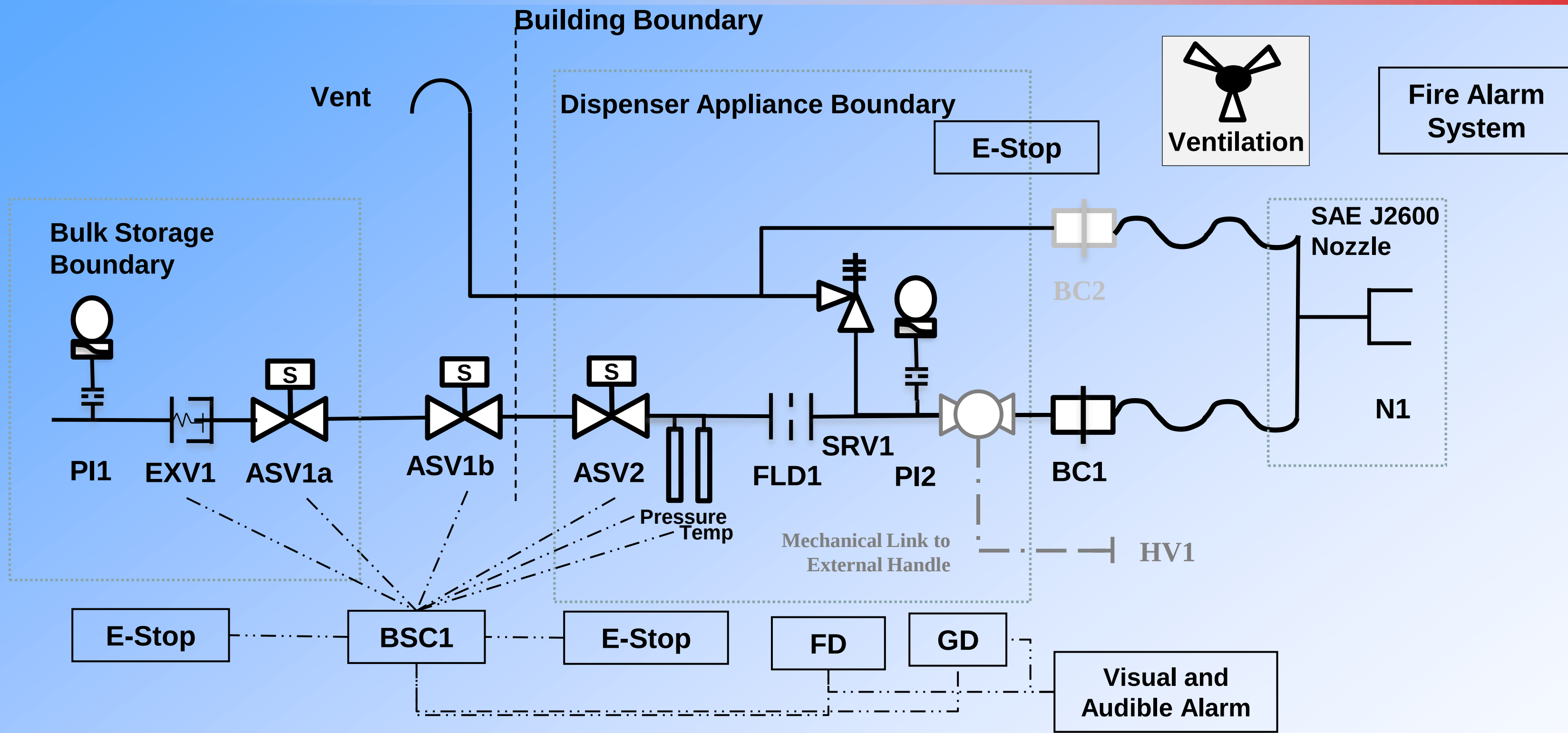
Risk from Indoor Refueling of Forklifts

- Representative refueling configurations were generated for evaluating risk
- Potential accidents identified using an FMEA
- Limited data from indoor refueling experience used in risk evaluation
- Scaled experiments have been performed to provide model validation data for full-scale FUEGO and FLACS simulations of hydrogen releases in warehouses.

Comparison of Simulation and Data for H_2 Concentration (with and without active ventilation)



Generic Indoor Dispenser



Generic systems modeled are code compliant

Dispensing rate: 0.5kg/min
Dispenser operates for up to 5min per refueling event.
Pressure from cascade storage: 6000psig
Dispensing pressure: 5000psig (350bar)
Operating temperature: 70F

<u>Other Safety Requirements</u>

- Physical Protection – 7.17.7.3
- Ignition Source Control – 7.1.23
- Explosion control- 6.9 when quantity exceeds quantities in Table 6.4.1.1
- Occupancy – 6.1.1.4, 7.1.1.3
- Qualified Operator – 10.3.3.1.1
- Minimum Room Volume – Table 10.3.3.2.2.2, 10.3.3.2.2.2 (D) for multiple dispensers
- Ceiling height – 10.3.3.2.2.2 (E)

Facility Description

- Facility is a generic 100,000m^3 dry food distribution warehouse.
  - A single dispenser is centered on the ground floor of the warehouse
  - Dispensing rate: 0.5kg/min
  - Pressure from cascade storage: 6000psig
  - Dispensing pressure: 5000psig (350bar)
- 20 vehicles in the fleet
  - Each vehicle holds 1kg of GH2; fully refueled once every 12 hours.
- 50 employees in the warehouse at all times
  - Warehouse personnel each work 2000 hours per year.

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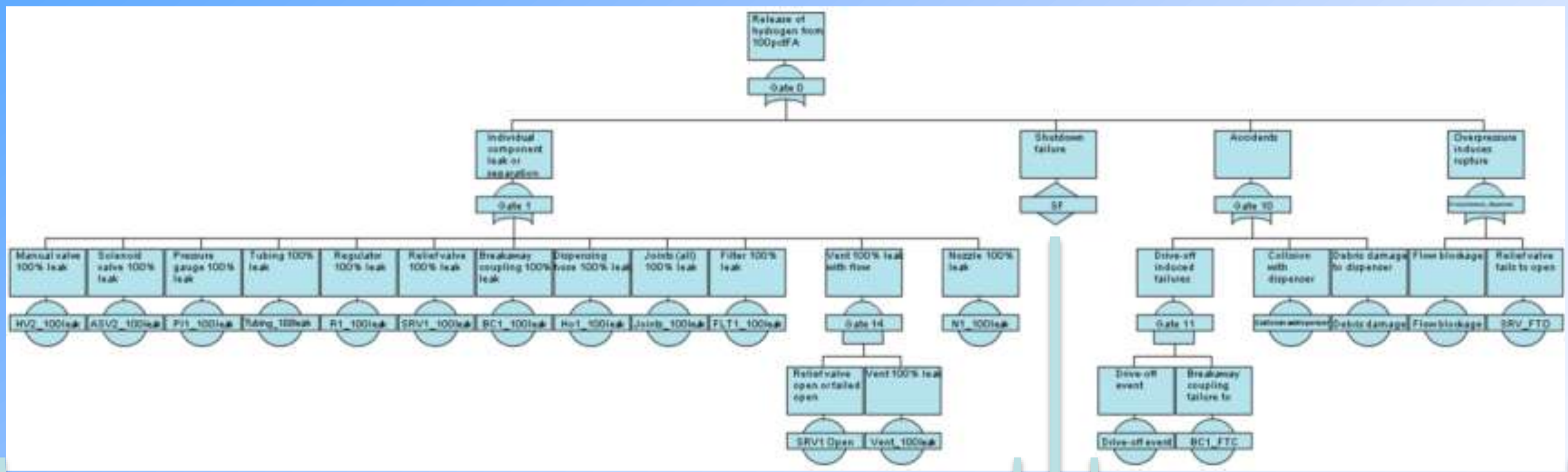
Release Causes



Individual component leaks

Shutdown failures

Accidents & Overpressure

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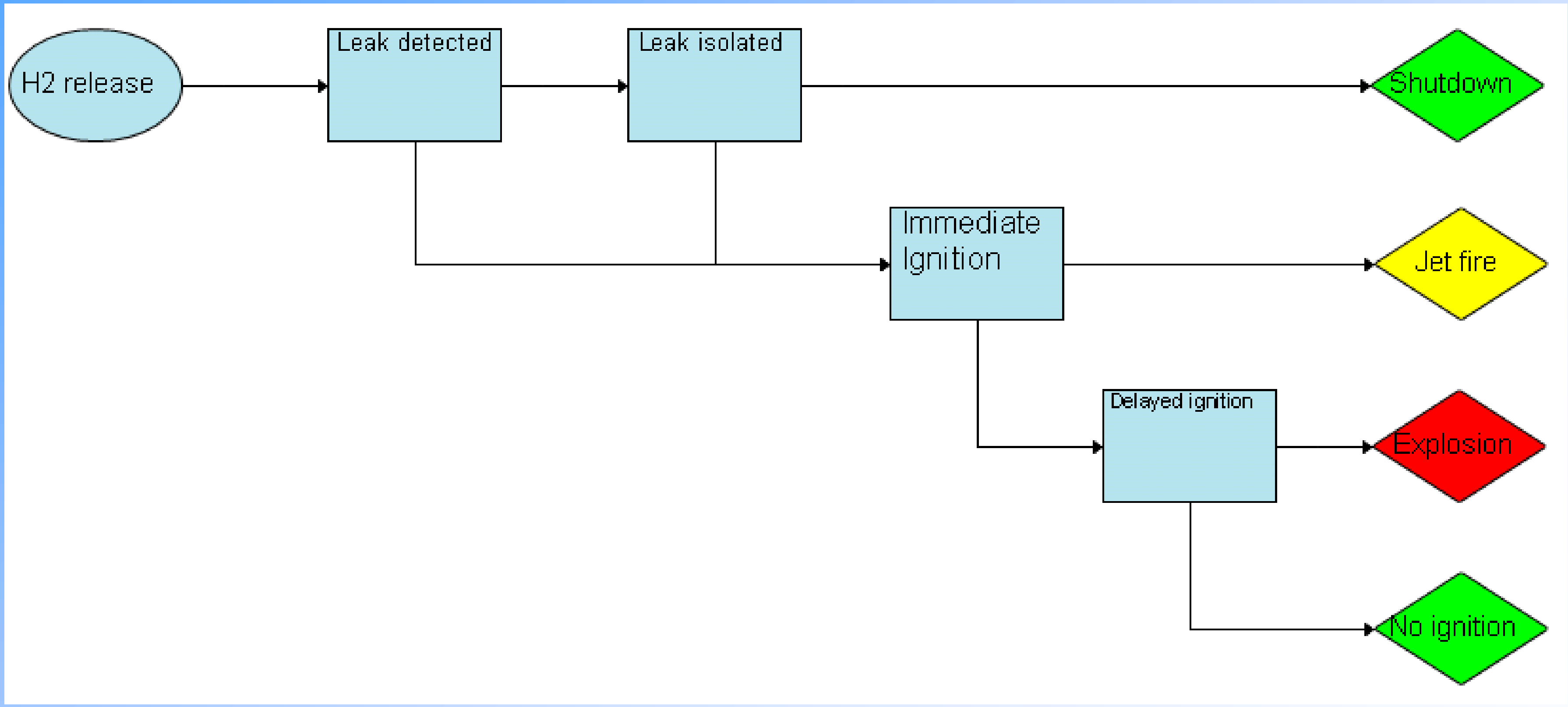
Release Scenarios



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

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

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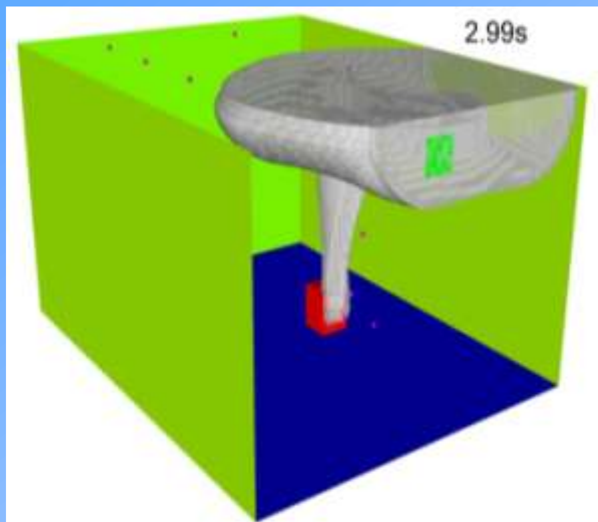
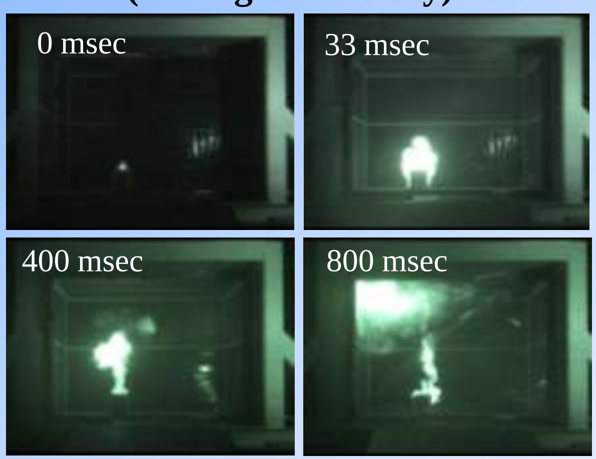
Scenarios Probabilities

Release size	Jet fire	Explosion
0.01%	2.51×10^{-4}	1.24×10^{-4}
0.10%	3.62×10^{-5}	1.80×10^{-5}
1%	1.09×10^{-5}	5.39×10^{-6}
10%	8.51×10^{-6}	4.22×10^{-6}
100%	3.66×10^{-5}	1.77×10^{-5}

Experimental Scenario Analysis and CFD Modeling Used to Evaluate Indoor Refueling Hazards.

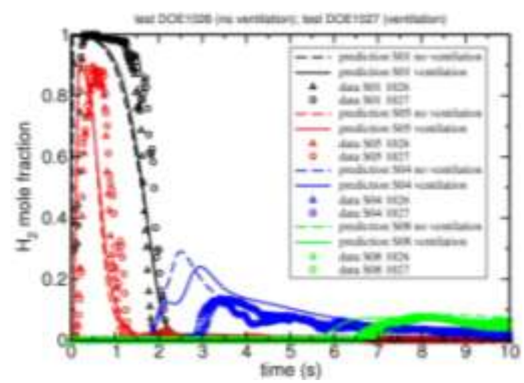


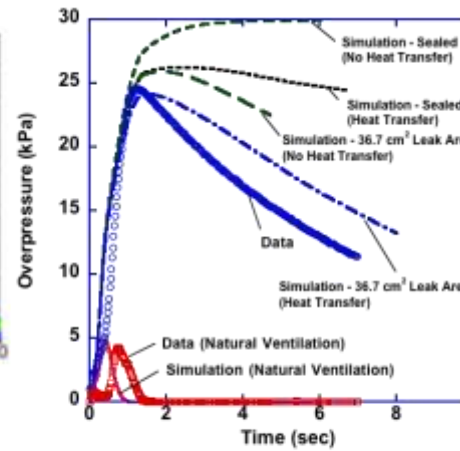
Flame front propagation imaged (3 sec ignition delay)



Large-scale experiments conducted in blast-hardened Sub-Scale Warehouse at SRI Test Site

Mitigation measures such as active/passive ventilation and blowout panels examined





CFD matched the data if wall heat transfer and warehouse leak area corrections were applied.

Indoor Refueling Results

- Fatal Accident Rate (FAR): 0.17 fatalities per 100 million industry hours
- Comparison to other industries (from Rausand, 2004):

Experienced FAR values for the Nordic Countries for the period 1980–1989.

Industry	FAR* (Fatalities per 10^8 working hours)
Agriculture, forestry, fishing and hunting	6.1
Raw material extraction	10.5
Industry, manufacturing	2.0
Electric, gas and water supply	5.0
Building and construction	5.0
Trade, restaurant and hotel	1.1
Transport, post and telecommunication	3.5
Banking and insurance	0.7
Private and public services, defense, etc.	0.6

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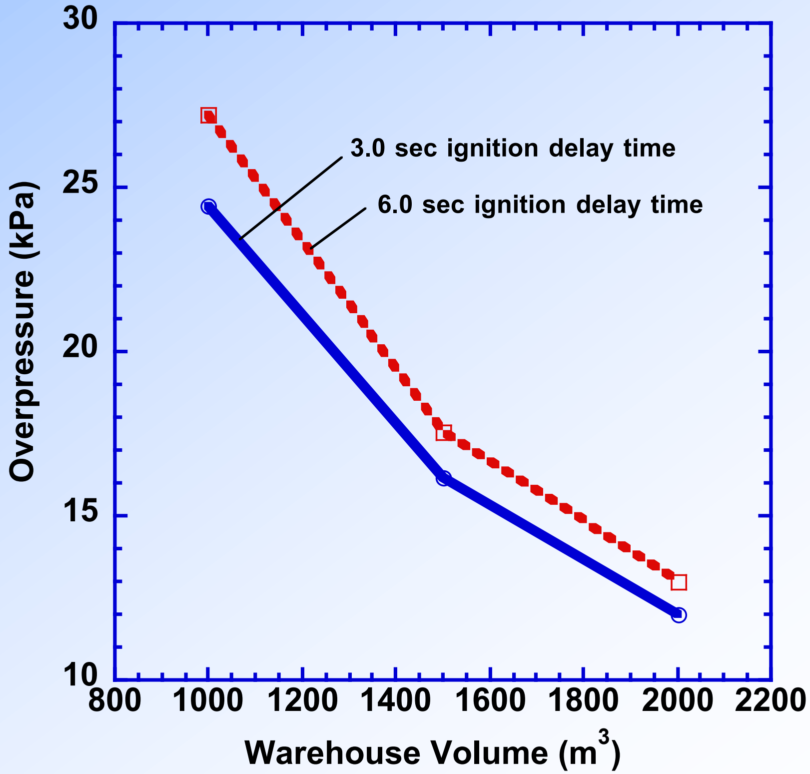
Forklift Results

- Average Individual Risk (AIR):
  - $AIR = H \cdot FAR \cdot 10^{-8}$ (where H is annual number of hours at work)
- 3.36e-06 fatalities/exposed person (1 in 30000)
  - (Recall, ALARP threshold of **$1x10^{-4}$/yr)**
- Compare to: 7.0e-5 fatalities/person for freight, stock, and material

Industry	Annual individual fatality risk level for employees
Deep sea fishermen on UK registered vessels	1 in 750
Extraction of mineral oil and gas	1 in 999
Extraction of minerals and ores	1 in 3,900
Coal extraction	1 in 7,100
Construction	1 in 10,200
Agriculture	1 in 13,500
Metal manufacturing industry	1 in 17,000

Input to Codes and Standards

- Results of indoor refueling QRA used to provide input to NFPA 2
  - NPFA 2 separation distances, warehouse ceiling height, room volume determined by QRA.
  - Development of generic system models identified vagueness in the NPFA 2 code, which will be resolved during 2013 code release.
  - Other changes to NFPA 2 Section 10 (refuelling) are in the works, using QRA models as a framework for understanding the trade-offs between various possible code requirements



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Research Needs

Accident frequency quantification:

- Need more data to produce H2-specific component failure frequencies. Need data on human errors and initiators.

Ignition:

- Need to develop a more robust ignition probability model
- Deterministic modeling and combined with ignition data enhances probability quantification & provides physical insight for focused risk reduction strategies

Consequences:

- Need first-order models to alleviate the need to run CFD codes to determine accident outcomes.

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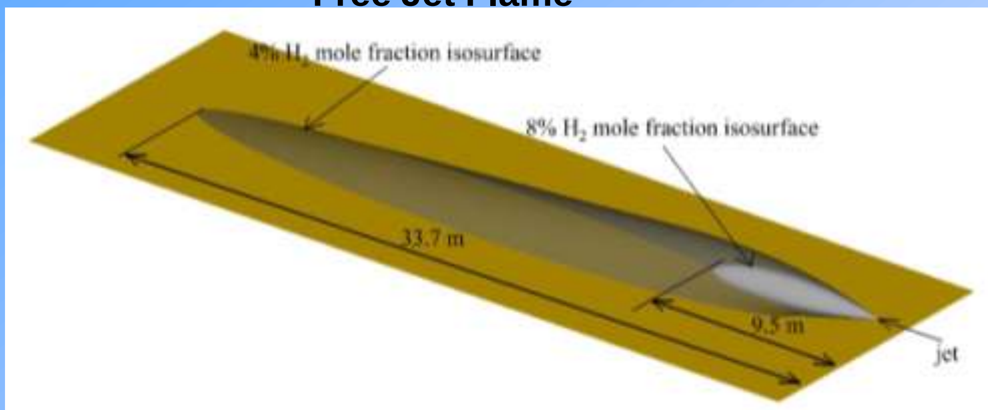
Backup Slides

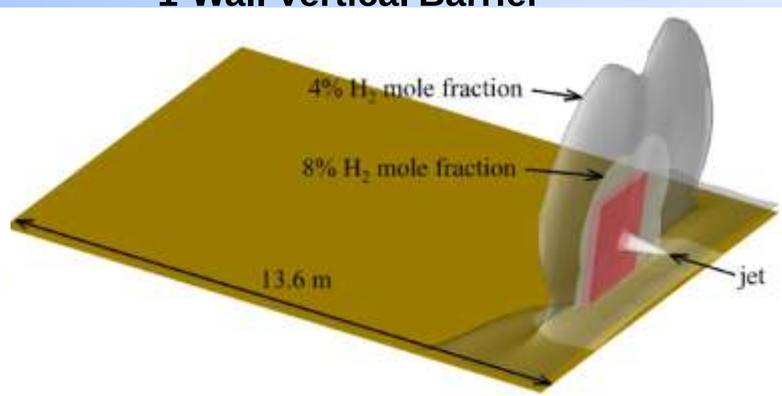
Effect on Hydrogen Envelope

Unignited hydrogen jets are essentially limited to a region close to the barrier, greatly reducing the axial extent of the unignited release. Lateral and vertical extent increases due to barrier.

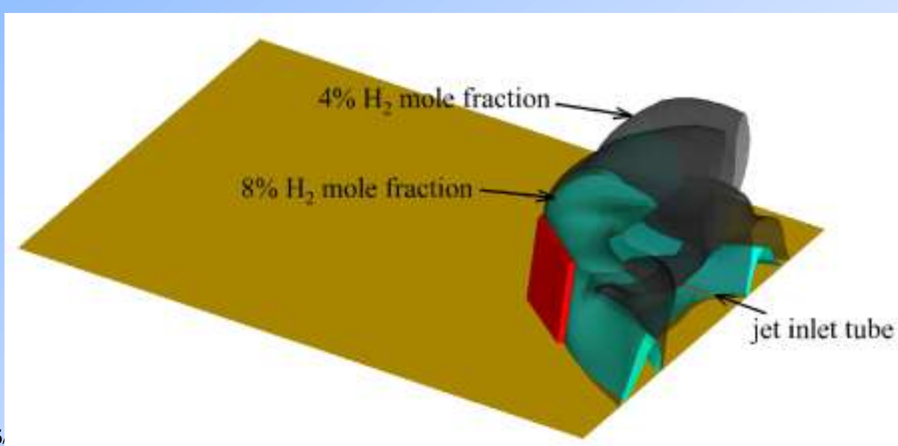
Free Jet Flame



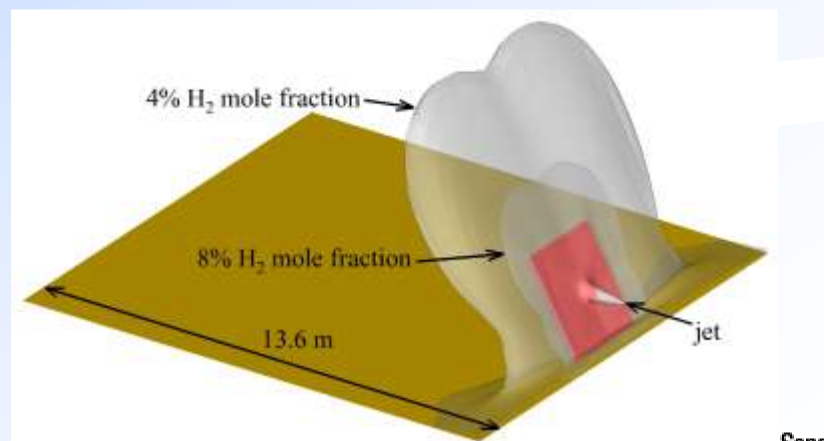
1-Wall Vertical Barrier



3-Wall Vertical Barrier

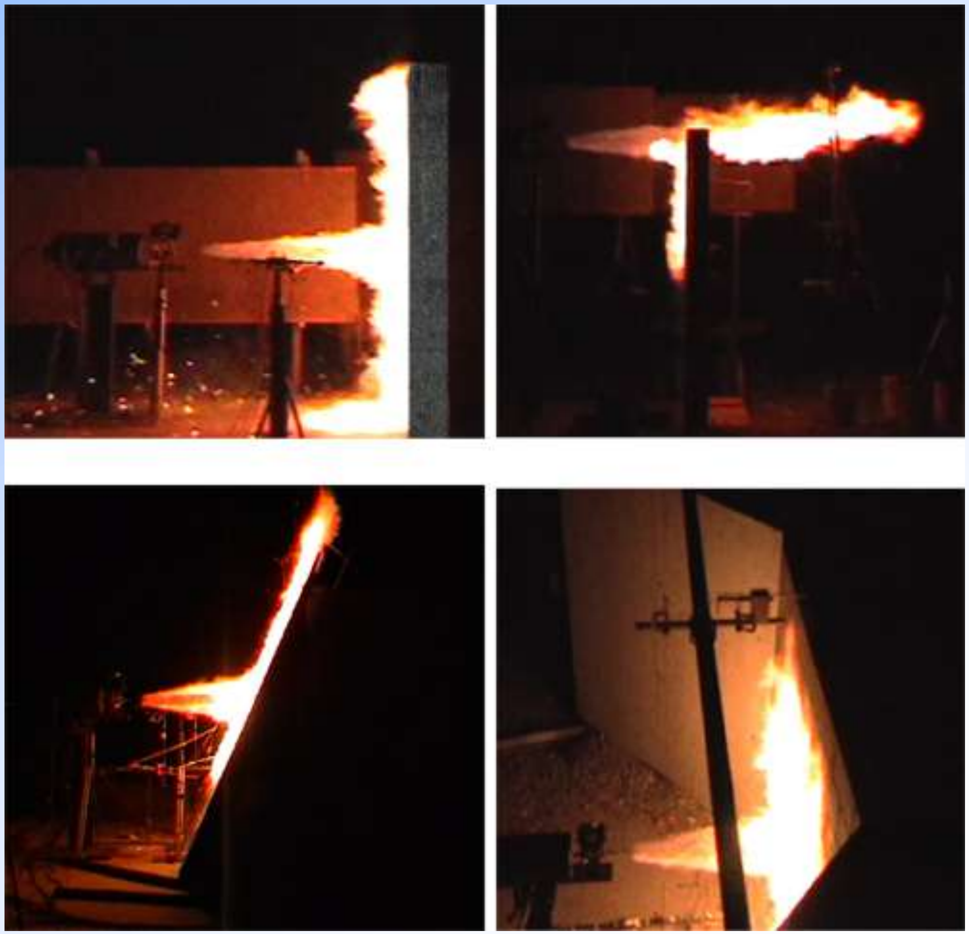


1-Wall Tilted Barrier



Direct Flame Effects

- Barriers are effective in reducing the downstream exposure to ignited hydrogen jets
- Some flame deflection back towards the hydrogen components can occur for straight barriers
- The height of the barrier is important for protecting potential targets



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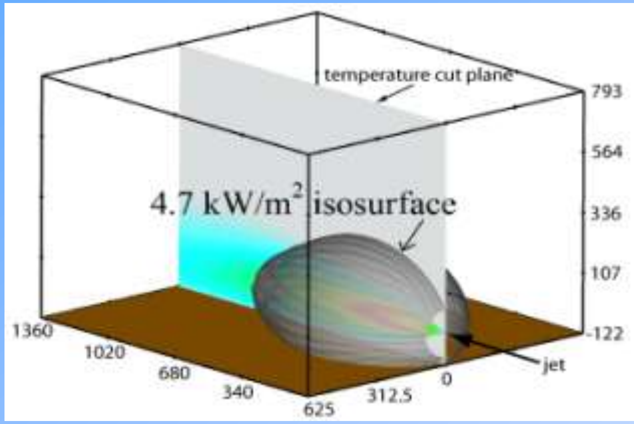
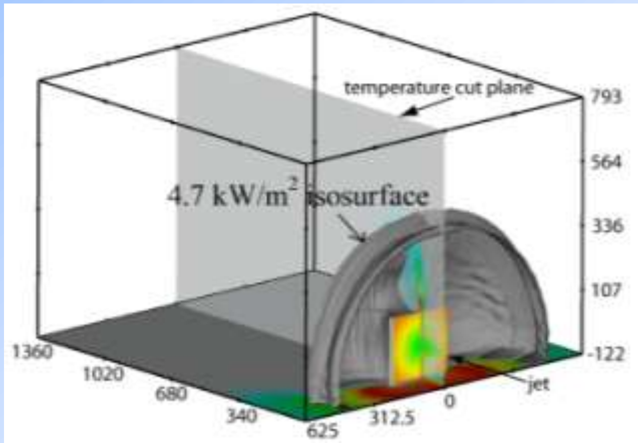
Thermal Radiation Reduction

Free jet

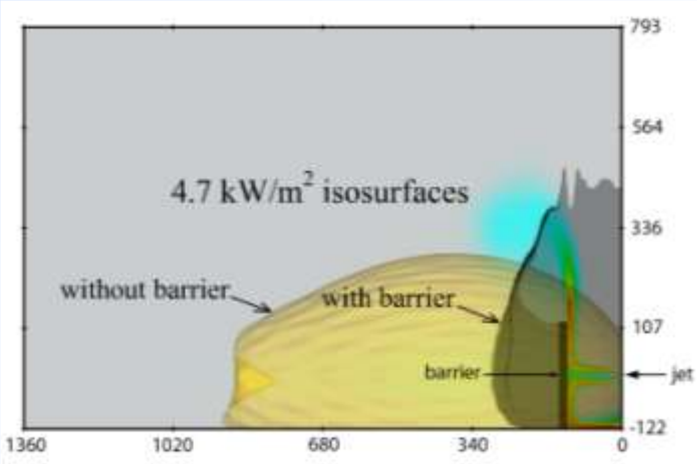


Single wall vertical barrier



- Hydrogen flames impinging on a barrier will be reshaped by barrier.
- Radiation downstream of the barrier from the reshaped flame contour can be greatly reduced (~3 fold reduction)
- Lateral and vertical extent of radiation isosurface can be greater than for a free jet with no barrier – requires proper design of barrier (can be specified in hydrogen C&S)

Comparison of isosurfaces



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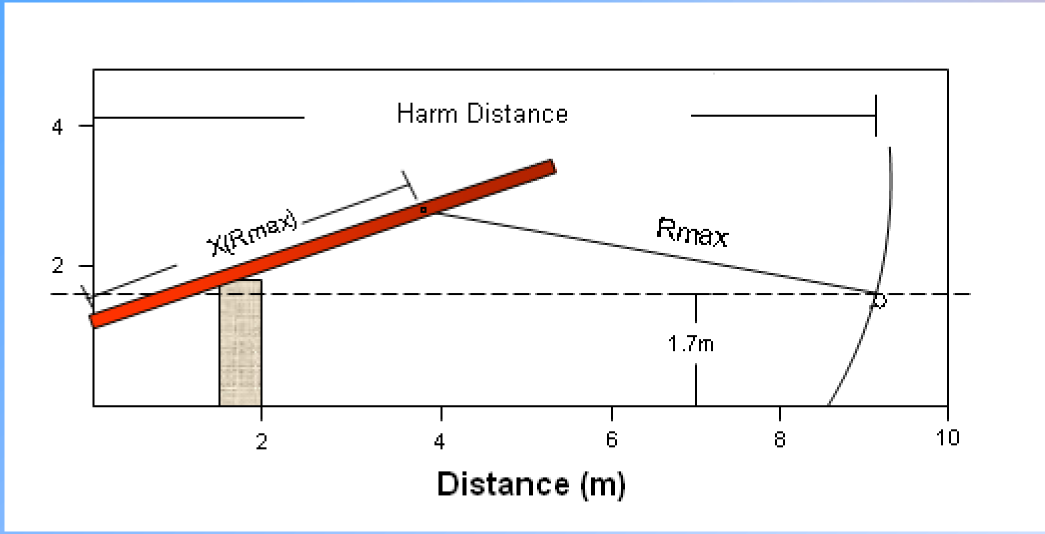
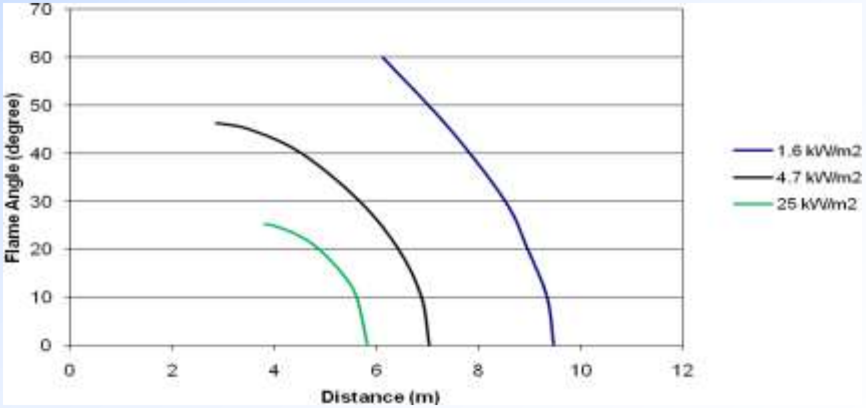
Thermal Radiation from Hydrogen Flames Directed Above Barrier



- Some fraction of hydrogen flames may be directed over top of the barrier
- Although direct contact with the flame may not occur, thermal radiation exposure is still possible

- Heat flux will decrease as the angle of the hydrogen jet passing over the barrier increases
- Harm distance will not substantially decrease for small angles (<30°)
- There is an angle at which a heat flux level will not occur for a specified target downstream of the barrier (can be specified in C&S)



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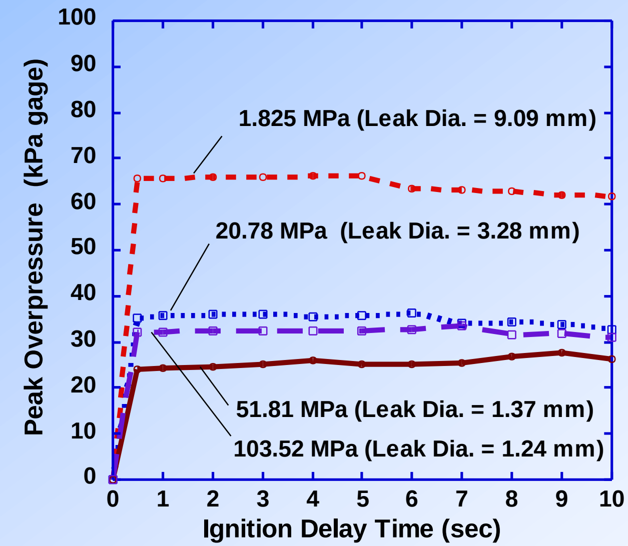
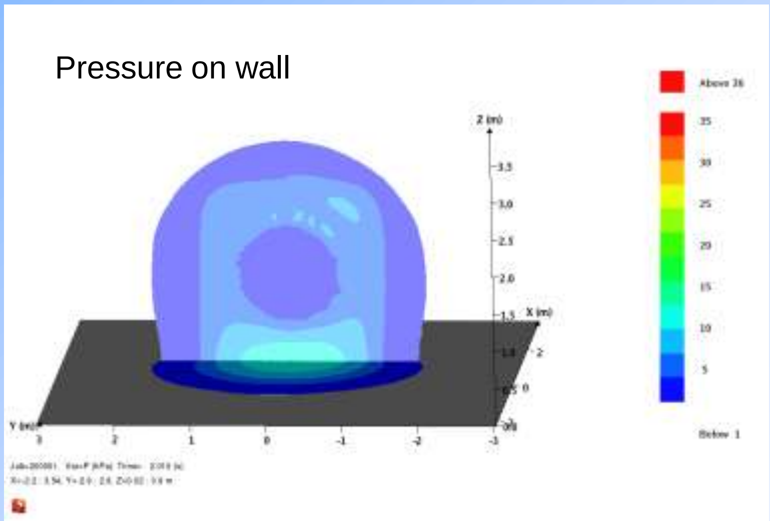
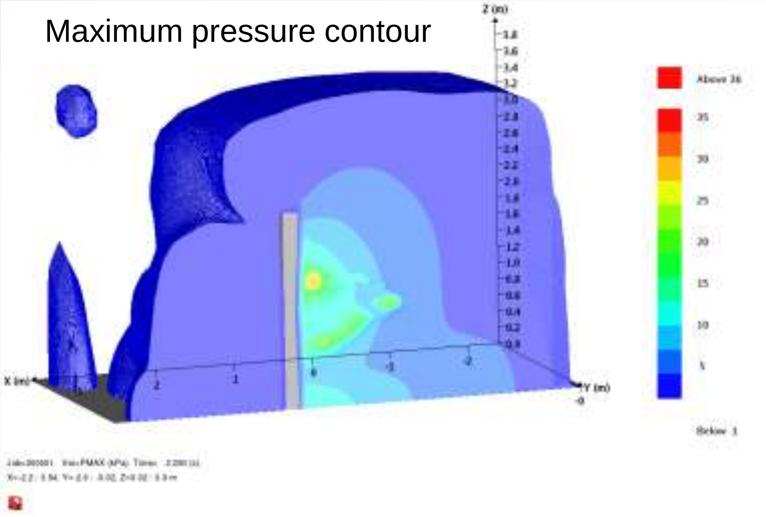
Overpressure Effects

- Barriers will result in higher pressures due to delayed ignition of hydrogen
- Although peak overpressures can be significant, average pressure and impulses on the barrier surface are small
- Pressure downstream of wall is small
- Potential harm to barrier and individuals is minimal







3.28 mm leak in 20.8 MPa system ignited at 2 s

Barrier Impacts on Hydrogen Releases

- Barriers between facility and the public eliminate risk from direct flame contact
- Reduces the axial extent of unignited jets significantly and associated risk if ignited; however, increases the lateral and vertical extent which increases 4% hydrogen envelope significantly
- Reduce the axial extent of thermal radiation from deflected flames significantly but increases vertical and lateral area of flame surface
- Thermal radiation from flames passing over the barrier can be reduced to low limits by increasing barrier height
- Overpressure from delayed ignition is not sufficient to challenge barrier integrity or harm individuals

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Consequence Summary

- Barriers between facility and the public eliminate risk from direct flame contact
- Reduces the axial extent of unignited jets significantly and associated risk if ignited; however, increases the lateral and vertical extent which increases 4% hydrogen envelope significantly
- Thermal radiation from deflected flames is reduced significantly
- Thermal radiation from flames passing over the barrier can be reduced to low limits by increasing barrier height
- Overpressure from delayed ignition is not sufficient to challenge barrier integrity or harm individuals

Risk Assessment Approach

- Used same facility model and risk assessment method as in SAND2009-0874, “Analysis to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards.” Allows for comparison of risk and separation distances with and without a barrier specified in NFPA-55.
- Single, vertical barrier wall was assumed to be 2.4 m high, sufficient in length to protect the public, and separated from the hydrogen equipment by 1.22 m (adequate to ensure protection from thermal heat flux from flames that extend over the top of the barrier).
- Overpressure on barrier determined to be insufficient to cause damage to barrier or hydrogen system. Overpressure downstream of barrier is insufficient to cause harm to public.
- Major risk contribution is associated with thermal radiation from deflected flames and delayed ignition of hydrogen envelope.

Risk Results

The use of barriers will reduce risk to a person at the lot line by a factor ~4 for the leak diameters used in NFPA-55.

System Pressure (MPa)	Leak Diameter[1] (mm)	Separation Distance to Facility Lot Line[2] w/o Barrier (m)	Individual Risk at Facility Lot Line (fatalities /yr)	
			w/o Barrier	Barrier
1.83	9.09	14.0	2.0E-5	5.4E-6
20.78	3.28	14.0	2.1E-5	5.5E-6
51.81	1.37	8.8	3.6E-5	1.1E-5
103.52	1.24	10.4	3.5E-5	1.0E-5

[1] Leak diameter corresponds to 3% of the largest flow area in the system
[2] Separation distance specified in NFPA-55, based on selected leak diameter.

Alternatively, barriers can be used to reduce the separation distance to the lot line. For a risk level equal to that without a barrier, the distance to the facility lot line can be decreased to ~3.5 m (measured from the barrier face) for the leak diameters shown above. Separation distance from the front of the barrier would be ~2 m.

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