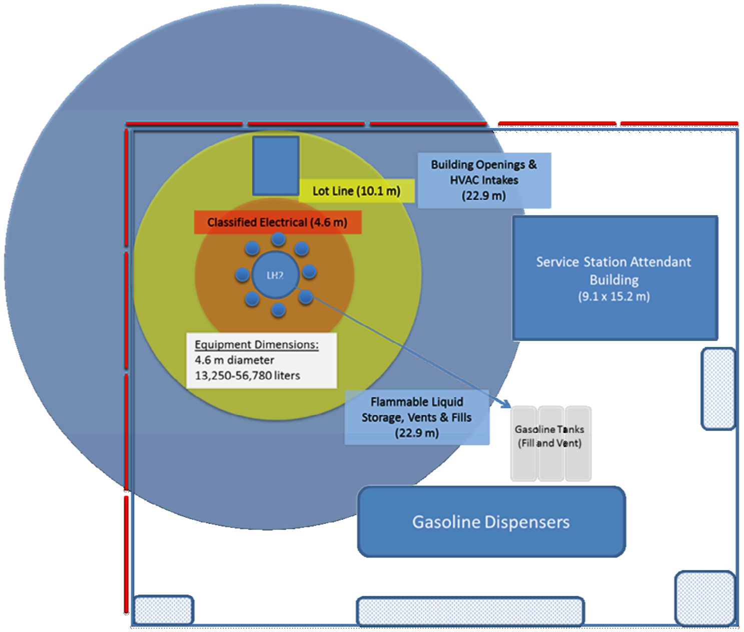
SAND2017-0836PE

Gaseous Hydrogen Separation Distances



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Sandia National Laboratories

January 24, 2017

SAND2017-XXXX

Outline

- Historical Separation Distances
- 2010 Risk-Informed Separation Distances
- Updates to 2010 Risk-Informed Separation Distances

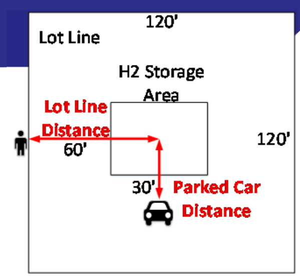
Historical Gaseous Separation Distances (pre-2010)

Type of Exposure	Separation Distance (m)				
	ICC International Fire Code (2003)	NFPA 55 (2005)			NFPA 52 (2006)
		Volume of $H_2 < 99\ m^3$	Volume of $H_2 = 99\ m^3$ to $425\ m^3$	Volume of $H_2 > 425\ m^3$	
Lot line	3.1	1.5	1.5	1.5	3.1
Outdoor public assembly	7.6	7.6	15.2	15.2	-
Offsite sidewalks and parked vehicles	4.6	4.6	4.6	4.6	3.1
Ignition sources	3.1	7.6	7.6	7.6	-
Building – Noncombustible walls	1.5[a] or 3.1[b]	0[b]	1.5[c] or 3.1[d]	1.5[c] or 7.6[d]	-
Building – Combustible walls	7.6[b]	3.1	7.6	15.2	
Above ground flammable or combustible liquid storage	6.1[e] or 15.2[f]	3.1[g] or 7.6[h]	3.1[g] or 7.6[h]	3.1[g] or 7.6[h]	
Below ground flammable or combustible liquid storage- vent or fill opening	6.1	7.6[g,h]	7.6[g,h]	7.6[g,h]	
Flammable gas storage above ground (other than hydrogen)	7.6[i] or 15.2[j]	3.1[k] or 7.6[l]	7.6[k] or 15.2[l]	7.6[k] or 15.2[l]	-

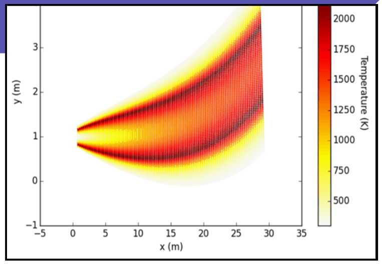
Before 2010, separation distance requirements were developed by expert judgment and based on total volume.

Creating Risk-Informed Separation Distances (2010 Ed. NFPA 55)

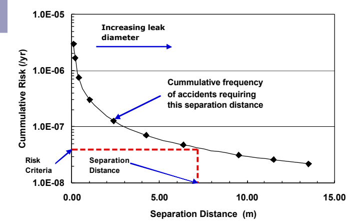
Identify exposures



Determine hazard scenario for each exposure



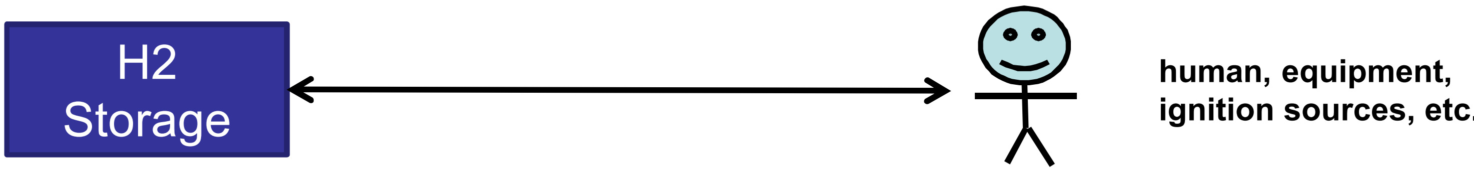
Determine separation distance for each exposure

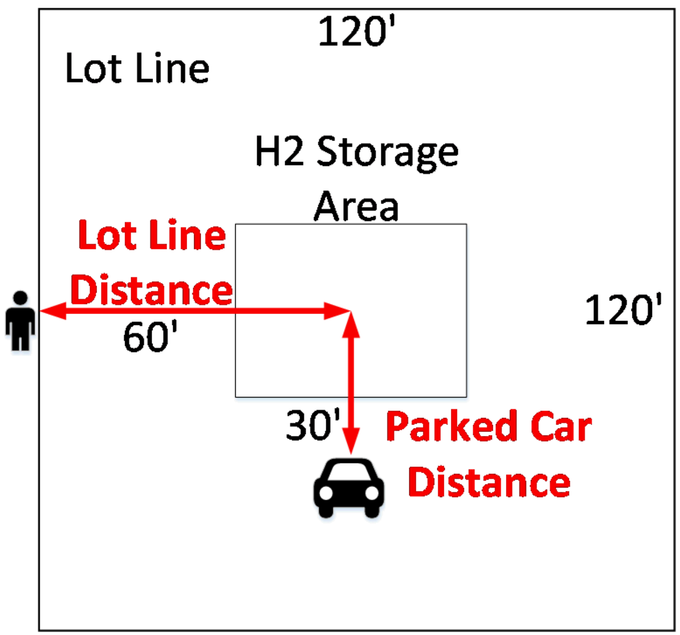


For more information, see Appendixes E and G in the 2010 Ed. of NFPA 55

Step 1: Identify Exposures

- Specified distances between a hazard source and a target





- Exposures can be:
  - Property lines
  - Exposed persons not involved in servicing the system
  - Air intakes
  - Parked vehicles
  - Public sidewalks
  - Other hazardous materials
  - Ignition sources
  - Wall openings
  - Utilities (overhead)

2. Determine Hazard Scenario for Each Exposure

- Each exposure identified was mapped to one or more hazard scenarios and subsequent harm criteria
- Design scenarios with their associated performance criteria and design scenarios were extracted from NFPA 1 for each hazard scenario

Exposure	Hazard Scenario(s)
Lot Lines	• Gas release and subsequent entrainment or accumulation by the receptor • Fire spread to or from adjacent equipment or structure • Gas explosion hazard on site or affecting adjacent property • Threat of injuries on site or adjacent property • Ignition of an unignited release/vented hydrogen
Exposed persons other than those involved in servicing of the system	• Threat of injuries on site or adjacent property
Ordinary Combustibles	• Fire spread to or from adjacent equipment or structure

Harm Criteria

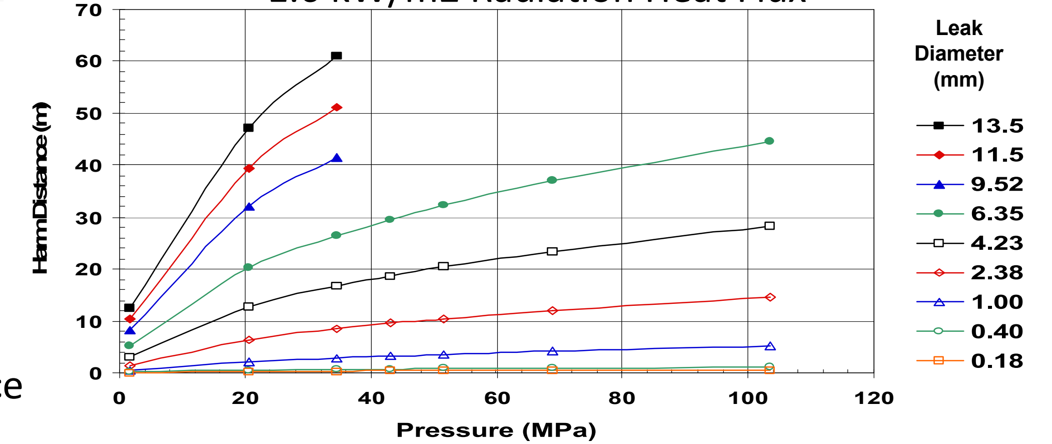
- Harm criteria was based on exposure type and:
  - Radiative heat flux
  - Unignited jet concentration distances
  - Visible flame length
- Using these distances based only on harm criteria is a consequence-based approach
- The task group determined that the probability of occurrence should also be considered in determining a reasonable level of safety

Exposure	Harm Criteria Examples	
Lot Lines	Unignited jet concentration decay distance to 4% mole fraction H2	Radiation heat flux level of 1577 W/m^2
Exposed Persons	Radiation heat flux level of 4732 W/m^2 for a maximum of 3 minutes	
Ordinary combustibles	Heat flux level of 20,000 W/m^2	Visible flame length

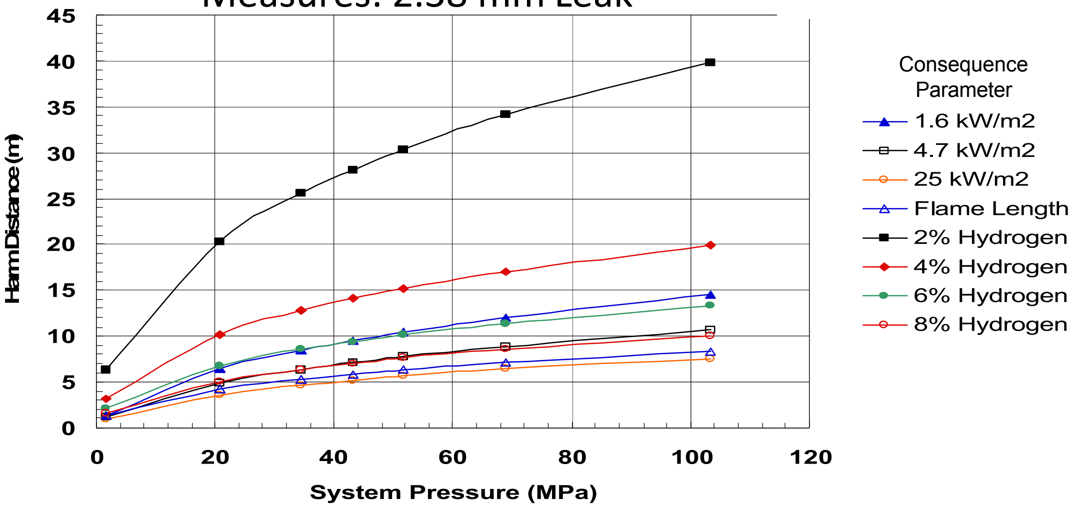
Consequence-Based Separation Distances Vary Significantly with Leak Diameter

- Sandia Hydrogen models were used to generate hazard distances for the harm criteria dependent on leak diameter

Hazard Distances for a Jet Fire: 1.6 kW/m2 Radiation Heat Flux



Hazard Distances for Different Consequence Measures: 2.38 mm Leak

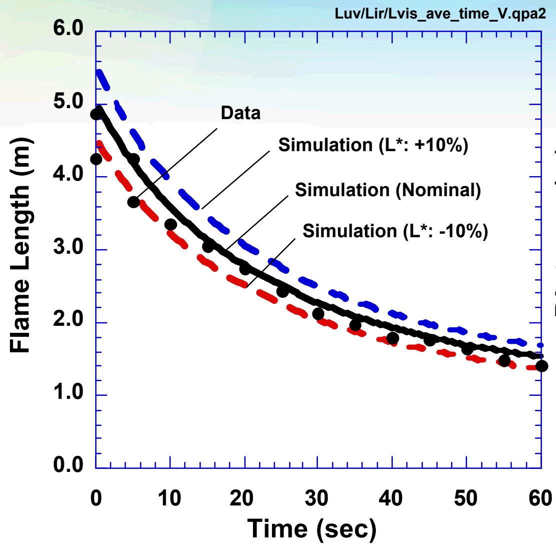


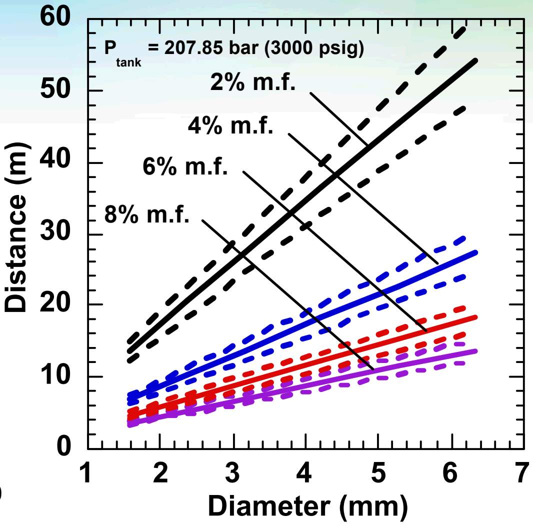
- Frequency and sizes of leaks were evaluated using industry failure data and Bayesian statistics

Can select leak diameter using a risk-informed approach

Sandia H2 Leak Model

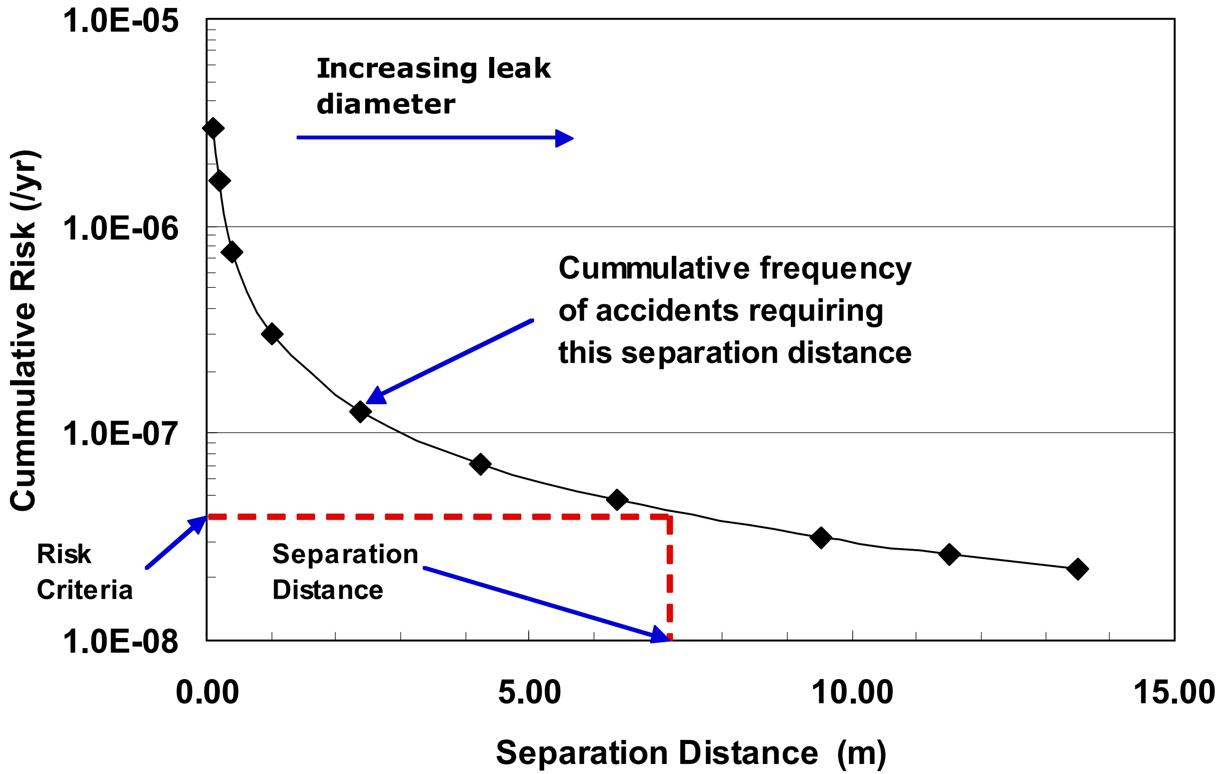
- Model predicts (as function of system volume, pressure, and leak size):
  - Radiant heat flux from hydrogen jet flames
  - Visible flame length for ignited jets
  - Hydrogen concentrations in jets
- Assumes circular orifice for leak geometry and constant pressure - conservative
- Model validated against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





3. Determine Separation Distance for Each Exposure

- The outcome is a risk-informed approach to creating separation distances



Selected Risk Guideline

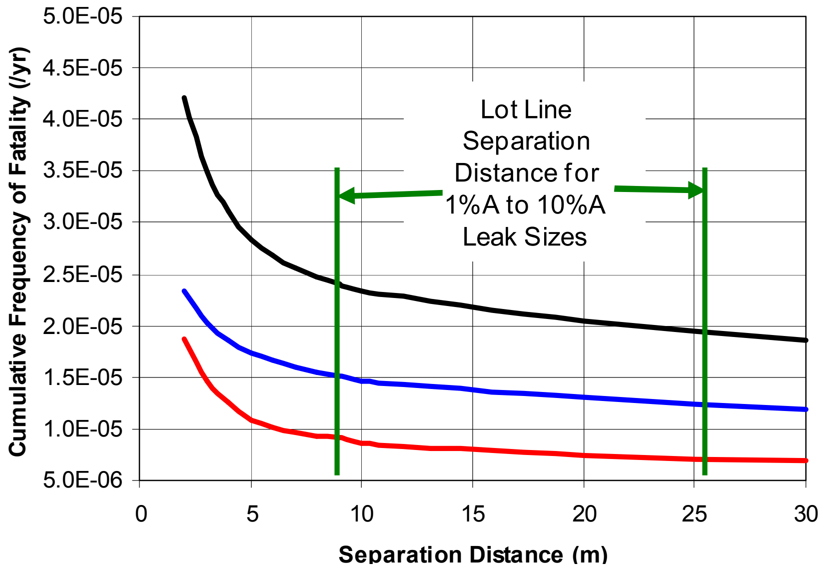
- Individual fatality risk to most exposed person at facility boundary selected for use in risk evaluation
- Use risk "Guideline" versus "Criteria"
  - Criteria varies for different countries and organizations
  - Making decisions based on comparison to hard risk criteria difficult because of uncertainties 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

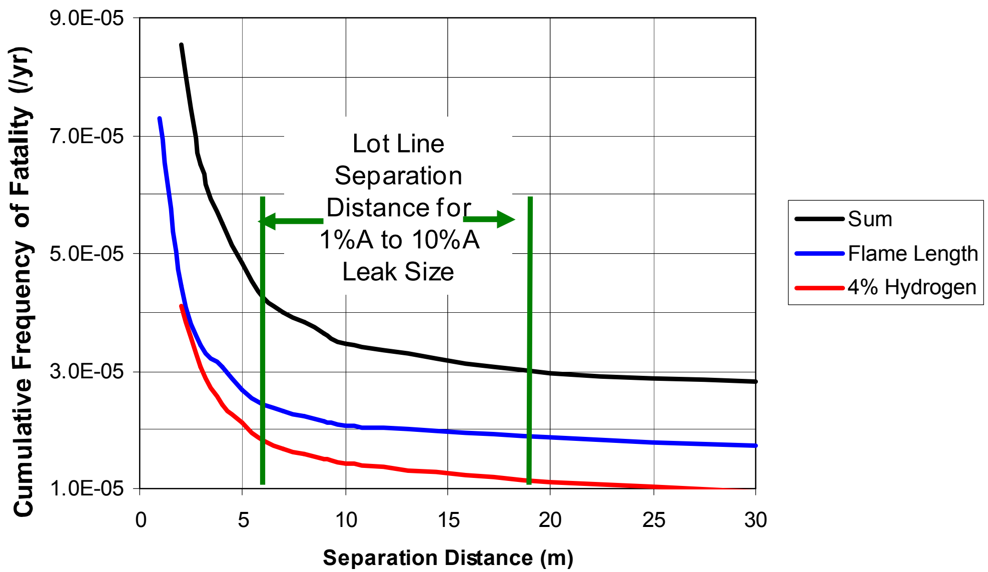
Basis – Comparative risk to gasoline stations, 10% of risk to society from all other accidents, 1E-5/yr is a value used by most countries that have established a risk criteria

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

Resulting Revisions to Gaseous Separation Distances

- Separation distances based on Pressure and Pipe size
- Typical values provided in table in code
- Actual risk-based equation also in code to calculate for other pipe diameters.

Table 7.3.2.3.1.2(c) Separation Distance Based on Alternative Pipe or Tube Internal Diameters

Notes*	>15 to ≤250 psi (>103.4 to ≤1724 kPa)	>250 to ≤3000 psi (>1724 to ≤ 20,684 kPa)	>3000 to ≤7500 psi (>20,684 ≤ 51,711 kPa)	>7500 to ≤15,000 psi (>51,711 ≤ 103,421 kPa)
(a)	$D_a = 0.23179d^{0.99931}$	$D_a = 0.73903d^{0.99962}$	$D_a = 1.1062d^{0.99959}$	$D_a = 1.4507d^{0.9995}$
(b)	$D_b = 0.091137d^{1.1303} + e^{-0.084081d}(0.087694d^{0.72681} - 0.091137d^{1.1303})$	$D_b = 0.36599d^{1.1152} + e^{-0.10771d}(0.1885d^{1.2531} - 0.36599d^{1.1152})$	$D_b = 0.60173d^{1.1063} + e^{-0.36516d}(-0.00002521d^{5.6078} - 0.60173d^{1.1063})$	$D_b = 0.84053d^{1.1023} + e^{-0.40365d}(-0.000043007d^{5.7146} - 0.84053d^{1.1023})$
(c)	$D_c = 0.075952d^{1.1022} + e^{-0.087589d}(0.076814d^{0.83088} - 0.075952d^{1.1022})$	$D_c = 0.2889d^{1.092} + e^{-0.10392d}(0.18705d^{1.1795} - 0.2889d^{1.092})$	$D_c = 0.45889d^{1.0887} + e^{-0.46723d}(-0.000027772d^{5.8841} - 0.45889d^{1.0887})$	$D_c = 0.6324d^{1.0859} + e^{-0.52477d}(-0.000086234d^{5.8213} - 0.6324d^{1.0859})$
(d)	$D_d = 0.096359d^{0.99928}$	$D_d = 0.3072d^{0.99962}$	$D_d = 0.45967d^{0.99971}$	$D_d = 0.60297d^{0.99956}$
(e)	$D_e = 0.096359d^{0.99928}$	$D_e = 0.3072d^{0.99962}$	$D_e = 0.45967d^{0.99971}$	$D_e = 0.60297d^{0.99956}$

Notes:

Table 7.3.2.3.1.2(b) Minimum Distance from Outdoor [GH_2] Systems to Exposures (SI Units)

	Exposure	>103.4 to ≤172.4 kPa 52.50 mm ID (m)	>1724 to ≤20,684 kPa 18.97 mm ID (m)	>20,684 ≤ to 51,711 kPa 7.92 mm ID (m)	>51,711 to ≤103,421 kPa 7.16 mm ID (m)
(1)	Lot lines[greater of a or b]	12.2	13.8	9.2	10.7
(2)	Exposed persons other than those involved in servicing of the system[c]	6.1	7.7	4.6	4.6
(3)	Buildings and structures				
	Combustible construction[d]	4.6	6.1	3.1	4.6
	Noncombustible non-fire-rated construction[e]	4.6	6.1	3.1	4.6
	Fire-rated construction with a fire resistance rating of not less than 2 hours[f]	1.6	1.6	1.6	1.6
(4)	Openings in buildings of fire-rated or non-fire-rated construction (doors, windows, and penetrations)				
	Openable[d]				
	Fire-rated or non-fire-rated	12.2	13.8	9.2	10.7
	Unopenable[c]				

Updates to Separation Distance Tables - 2016

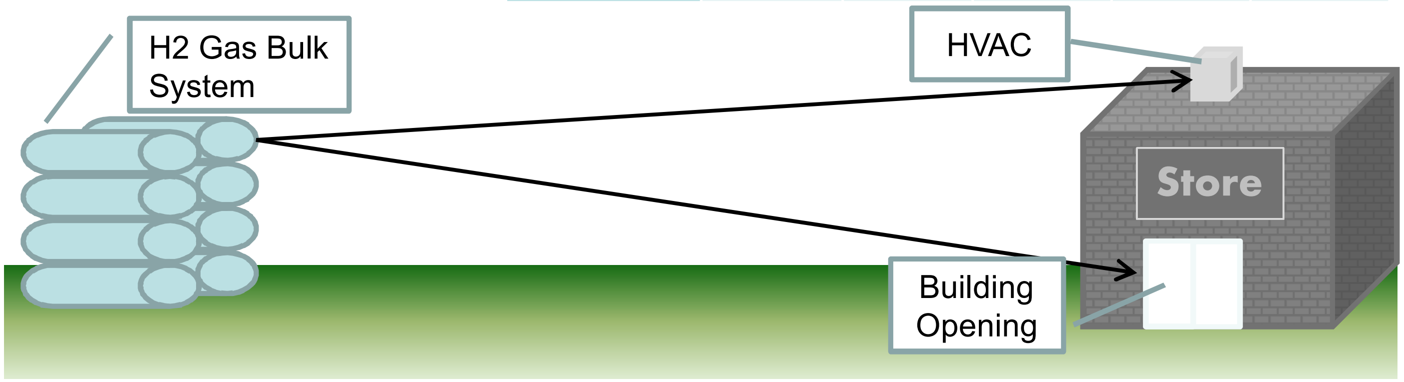
- Three key decisions were made by the task group for the 2010 Edition of NFPA 55 that were reevaluated for the latest edition of NFPA 55:
  - Changed the internal pipe diameter leak size from 3% to 1% to remove excess conservatism
    - This accounts for 95% of leakage frequency from the example systems
  - Changed the 'no harm' criteria of 1.6 kW/m^2 to 4.7 kW/m^2
    - The 1.6kW/m^2 assumed that exposed persons will not take protective actions, such as relocating from the fire scene
  - Hydrogen concentration threshold changed from 4% to 8% based on work performed at Sandia
- Because of the removal of the excess conservatism, the task group decided to add a safety factor of 1.5 to the safety distance

Updates to Separation Distance Tables

- Key decisions were made by the task group for the 2010 Edition of NFPA 55 that were reevaluated for the latest edition of NFPA 55:
  - Unignited jet concentration from 4% to 8%
  - Heat Flux level from 1.6 kW/m^2 to 4.7 kW/m^2
  - Leak area from 3% to 1%
  - Added safety factor of 1.5

Exposures	Code Version	Separation Distance			
		>0.10 to 1.72 MPa	>1.72 to 20.68 MPa	>20.68 to 51.71 MPa	>51.71 to 103.43 MPa
Group 1 Exposures	2016	12 m	14 m	9 m	10 m
	2019	**5 m**	**6 m**	**4 m**	**5 m**
Group 2 Exposures	2016	6 m	7 m	4 m	5 m
	2019	**5 m**	**6 m**	**3 m**	**4 m**
Group 3 Exposures	2016	5 m	6 m	4 m	4 m
	2019	**4 m**	**5 m**	**3 m**	**4 m**

2016: 10 m for 70 MPa storage



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Group 3 Exposures	2016	5 m	6 m	4 m	4 m
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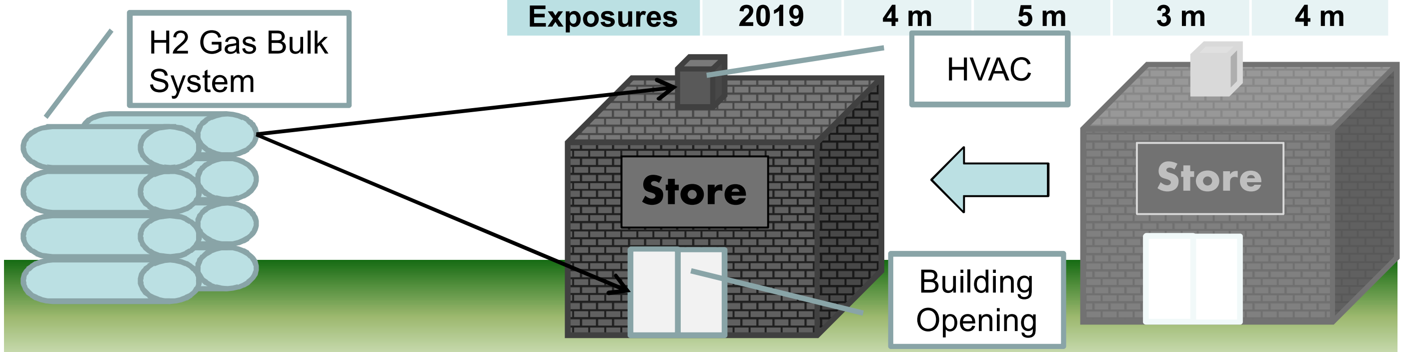
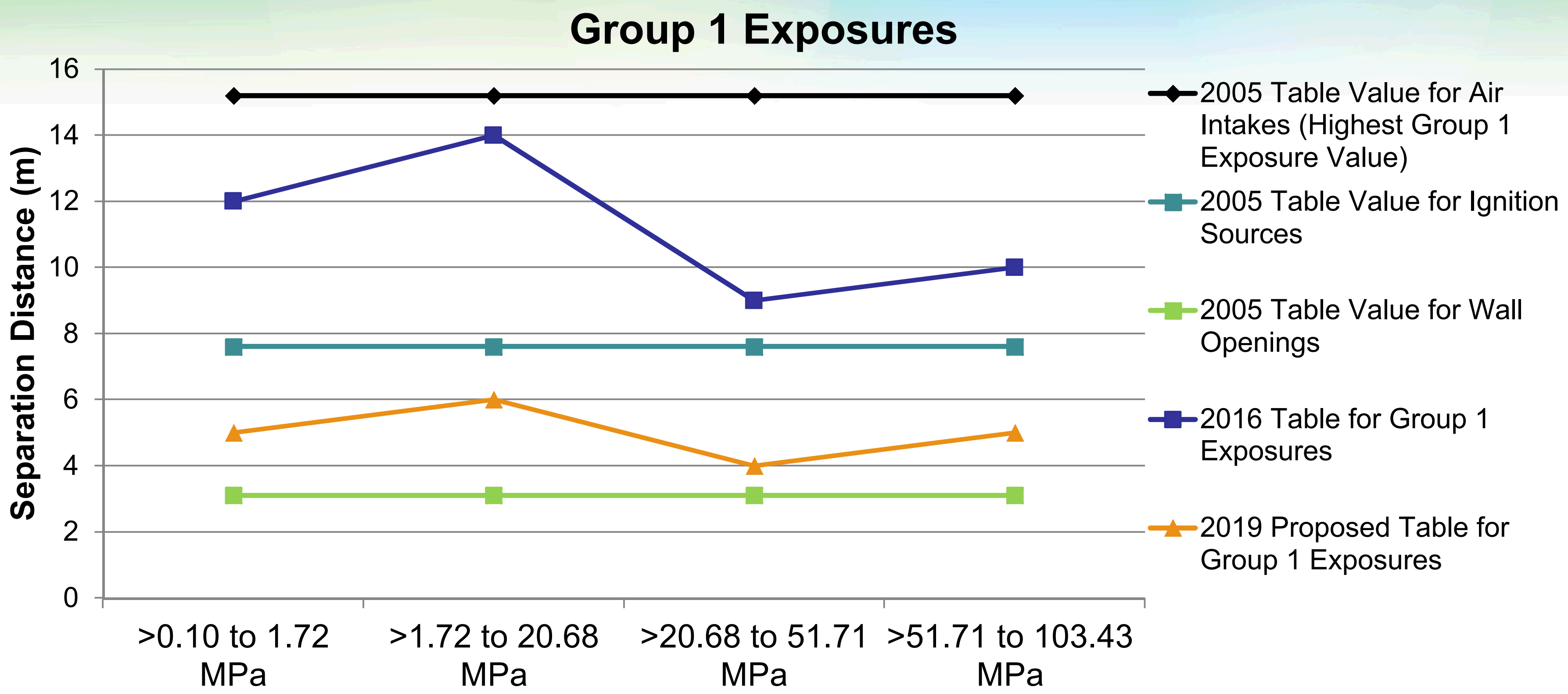
2016: 10 m for 70 MPa storage

2019: 5 m for 70 MPa storage



Risk-based code requirements based on proposed risk threshold revisions enable more sites to readily accept hydrogen infrastructure

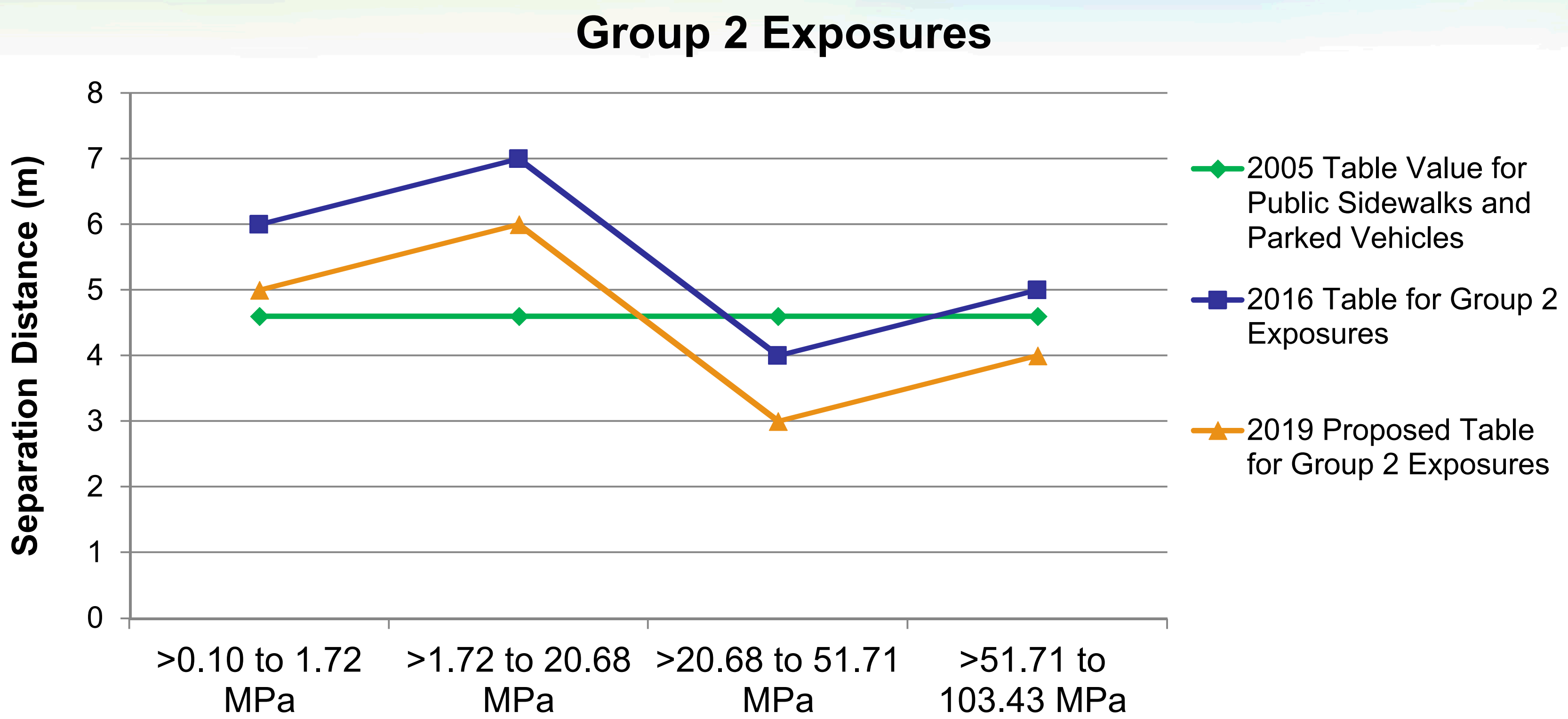
Separation Distance Reductions: Group 1 Exposures



Group 1 Exposures:

- Lot lines
- Air intakes
- Operable openings in buildings
- Ignition sources

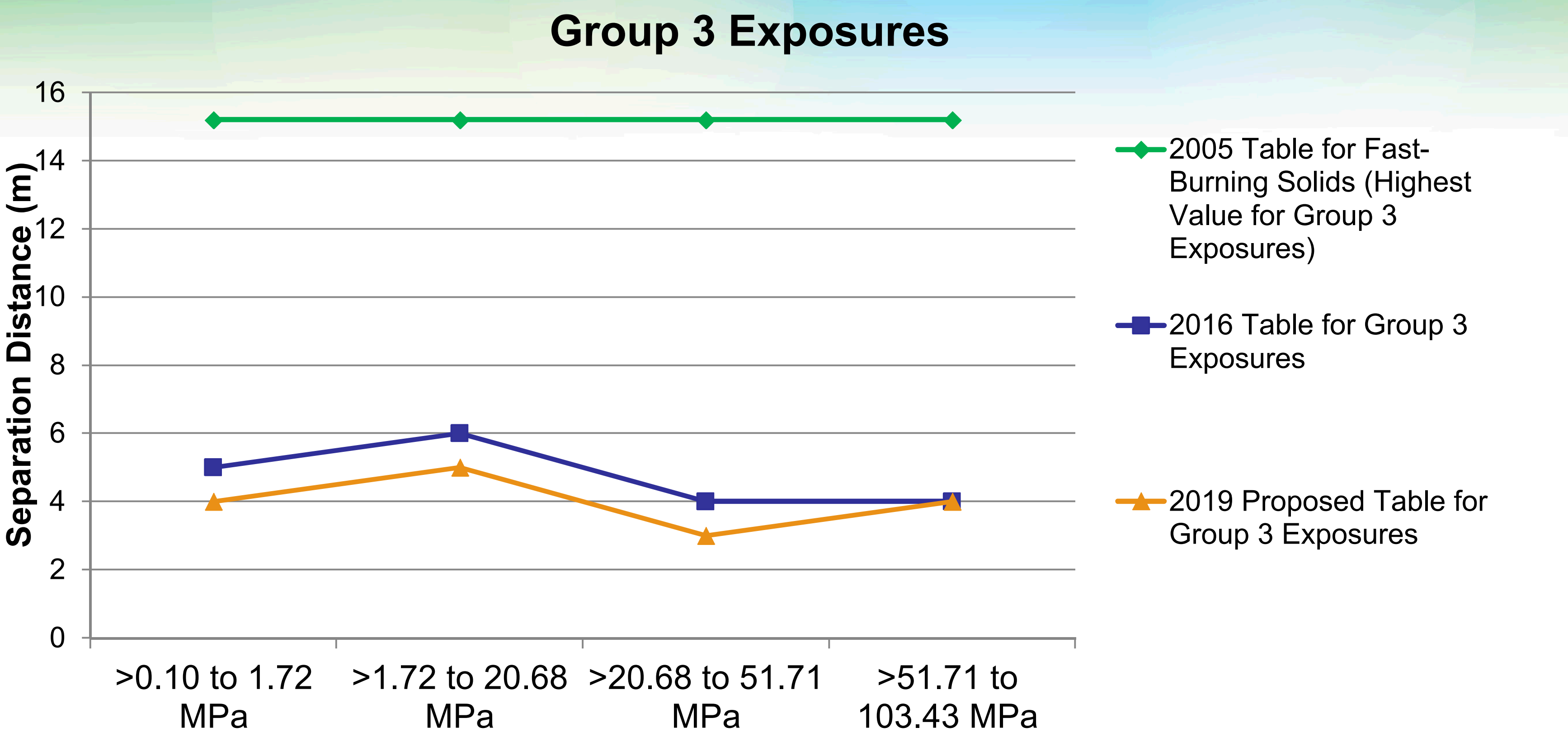
Separation Distance Reductions: Group 2 Exposures



Group 2 Exposures:

- Exposed persons other than those servicing the system
- Parked Cars

Separation Distance Reductions: Group 3 Exposures



Group 3 Exposures:

- Hazardous material storage systems
- Slow burning combustible solids
- Fast burning solids
- Overhead utilities
- Flammable gas metering, etc.

Summary

- Task group updated bulk hydrogen gaseous separation distances based on a risk-informed scientific approach for the 2010 Edition of NFPA 55
- NFPA 2/55 task group reviewed judgements made in the first iteration and removed excess conservatism from key judgements made earlier
- These numbers were approved by the larger NFPA 2/55 Committees in the first draft meeting in Fall 2016

For more information, see:

- 2010 Ed. NFPA 55, Appendix E & Appendix G
- SAND2009-0874

Back-Up Slides

Progress: Science-Based Prescriptive Requirement Revisions LH2

- Goal: Use QRA tools and methods to revise bulk liquid hydrogen system separation distances in NFPA 55/NFPA 2
- Progress:
  - The NFPA 55/2 hydrogen storage task group performed a risk analysis on a representative bulk liquefied hydrogen storage system and determined nine release scenarios with the highest risk
    - Six of the highest-risk scenarios are during liquid hydrogen transfer operations from a tanker truck to the bulk LH2 storage tank
    - Three scenarios are during normal system operations
  - Determined model inputs and risk criteria for the nine scenarios

Results of the risk analysis on the bulk liquefied hydrogen storage system will be fed into liquid hydrogen models

Details of LH2 Prescriptive Code Revision Scenario Selection and Prioritization

- CGA P-28 *OSHA Process Safety Management and EPA Risk Management Plan Guidance Document for Bulk Liquid Hydrogen Systems* was used as a basis for typical LH2 system definition and HAZOP scenario identification
- Each scenario was reviewed and assigned an Even Hazard and Hazard Severity value.
- Based on these values, the scenario was given a risk ranking which was used to prioritize the scenario

Event Likelihood Classification

Level	Annual Probability	Probability Description
1	Frequent > 1.0	Expected to occur once per year or more frequently.
2	Reasonably probable 1.0 to 0.1	Expected to occur once per 10 years.
3	Occasional 0.01 to 0.1	Expected to occur once per 100 years.
4	Remote 0.001 to 0.01	Expected to occur once per 1000 years.
5	Extremely remote 0.0001 to 0.001	Expected to occur once per 10,000 years.
6	Improbable < 0.0001	Expected to occur less than once per 10,000 years. Extremely unlikely to occur.

Hazard Severity Classification

Level	Description	Potential Consequences
1	Catastrophic	May cause fatality to non-associated members of the public.
2	Critical	May cause severe injury to non-associated members of the public, fatality or serious injury to works of the public, fatality or serious injury to workers of persons conducting business at a refueling site or significant damage to equipment/facilities.
3	Marginal	May cause minor injury, or minor system damage.
4	Negligible	Will not result in injury or system damage.

Risk Ranking:

Severity \ Likelihood	1	2	3	4	5	6
1	1	1	1	2	3	4
2	1	1	2	3	3	4
3	2	2	3	3	4	4
4	4	4	4	4	4	4

1: High Risk
2: Moderate Risk
3: Low Risk
4: Routine Risk

LH2 Prioritized Scenarios to be Used for Separation Distance Revision

	HAZOP Number and Description	
Release scenarios during liquid transfer to bulk storage tank	1.18	High flow of gaseous hydrogen from trailer vent stack due to venting excess pressure after LH2 transfer
	1.19	Normal flow from trailer vent stack due to venting excess pressure after LH2 transfer
	1.6	High flow from line rupture, valve or component failure during transfer process
	1.4	High temperature due to external fire causes high flow venting through tank vent stack
	1.8	Reverse flow during transfer process caused by human error and pressure mismanagement
	1.16	Loss of containment from external impacts, consider all causes

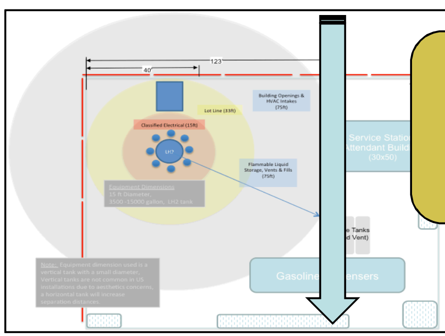
	HAZOP Number and Description	
Release scenarios during normal system operation	4.15	Loss of containment from pipe leading from tank to vaporizer or vaporizer itself caused by thermal cycles or ice falling from vaporizers
	6.15	Misdirected flow caused by operator error resulting in large low level release of cold gaseous hydrogen through bottom drain valve of vent stack during normal tank venting process
	2.1	High pressure because of a leak in inner vessel allowing hydrogen into the vacuum area

Approach: Application of QRA to Performance-Based Design

Performance-Based Design of Refueling Station

Representative Station: **H2FIRST Reference Liquid Station**

- Meets all Prescriptive Requirements
- Calculate Benchmark Performance Criteria



- Modifies Key Requirements
- Incorporate Mitigating Factors
- Calculate Risk Risk Equivalent Performance Criteria

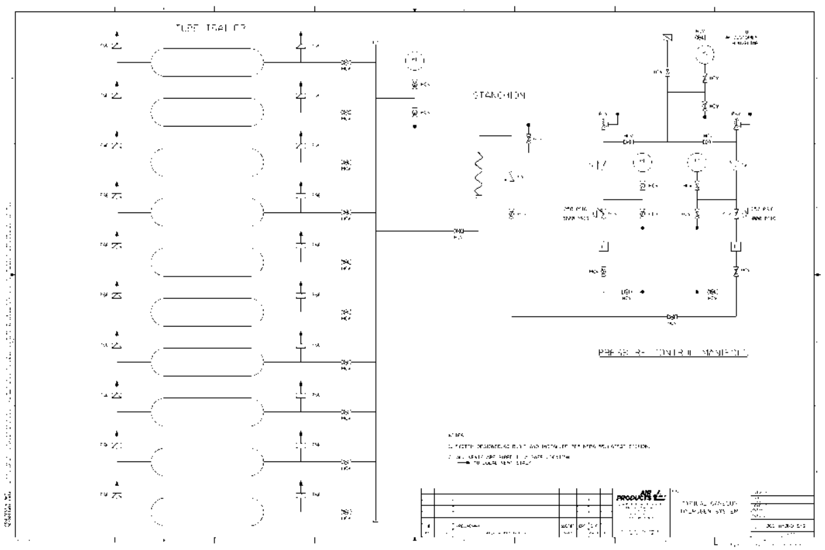
Vet with H2 Code Industry and Stakeholders

Real-World Station: **Linde Foster City**

- Modifies One Key Requirement and Incorporates Mitigating Factors
- Prepare Performance-Based Design Report and Documentation Utilizing HyRAM QRA Toolkit
- Follows Real-World Permitting Process

Risk-Informed Approach to Select Leak Diameter

- Examined appropriate leakage data to determine leak size distribution
  - Selected leak size



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:

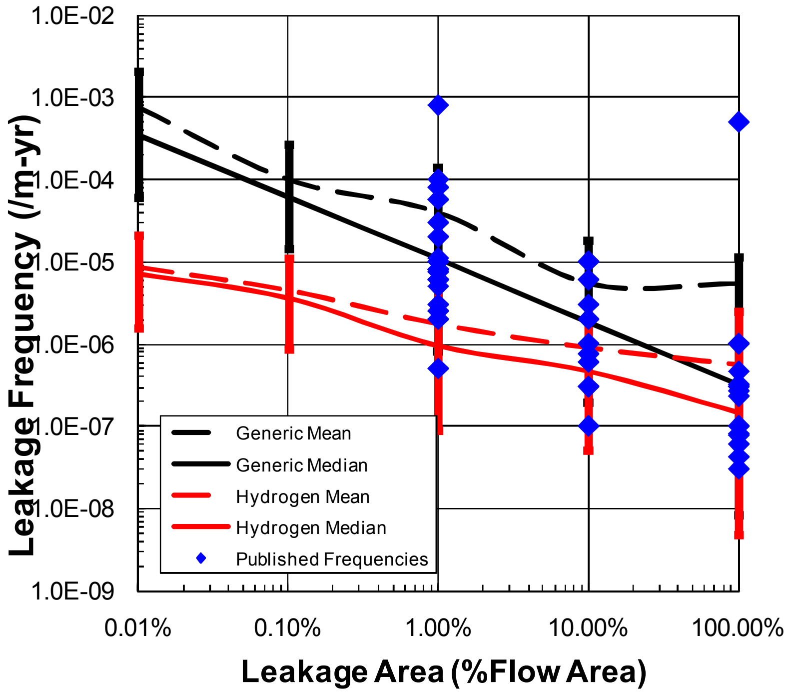
- Not enough for traditional statistical approach
- Instead, representative values are selected from other industries (oil and gas)

Problems with this approach:

- Not hydrogen specific
- Parameter uncertainty distribution is uncharacterized

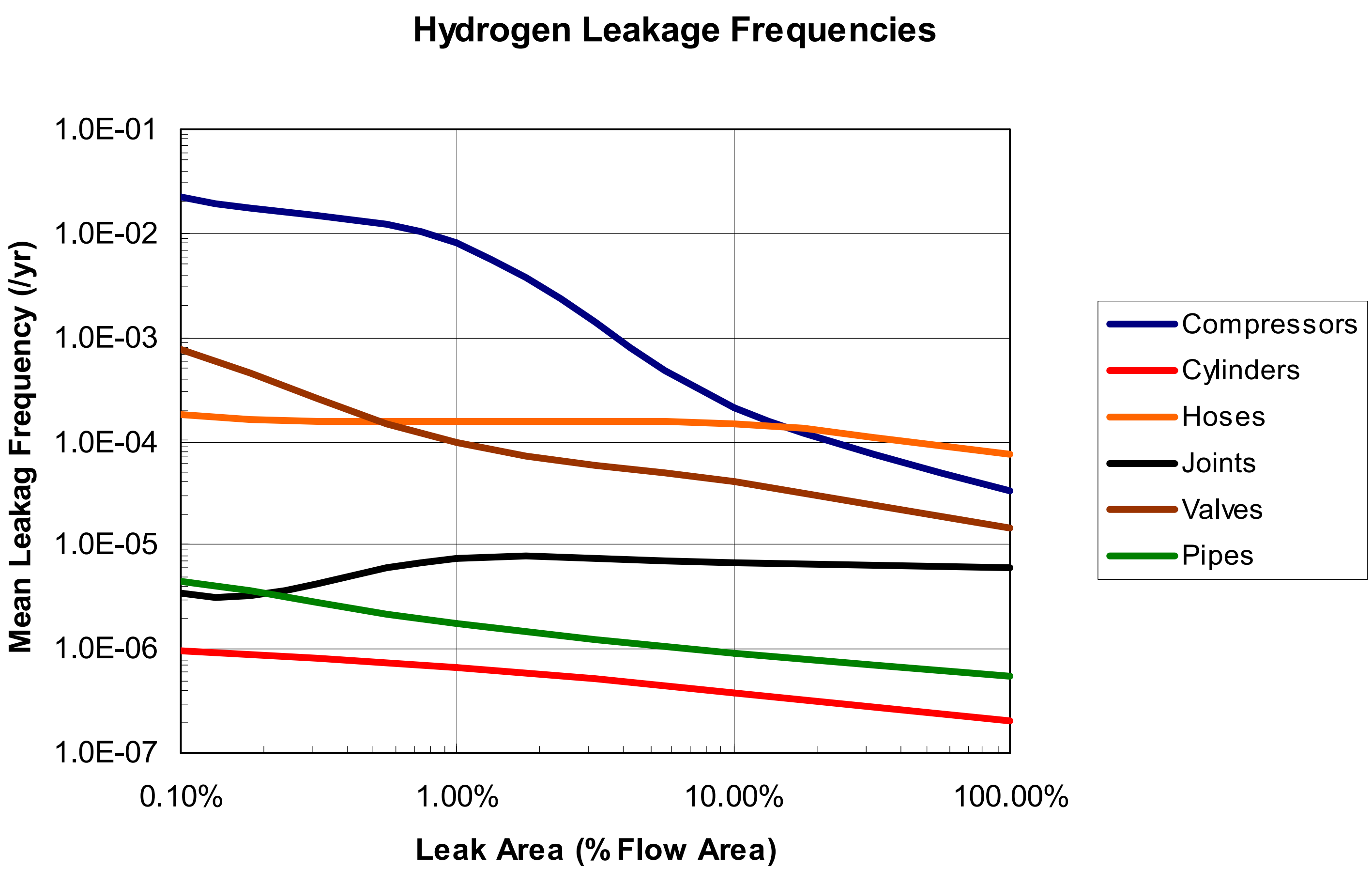
Solution:

- 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



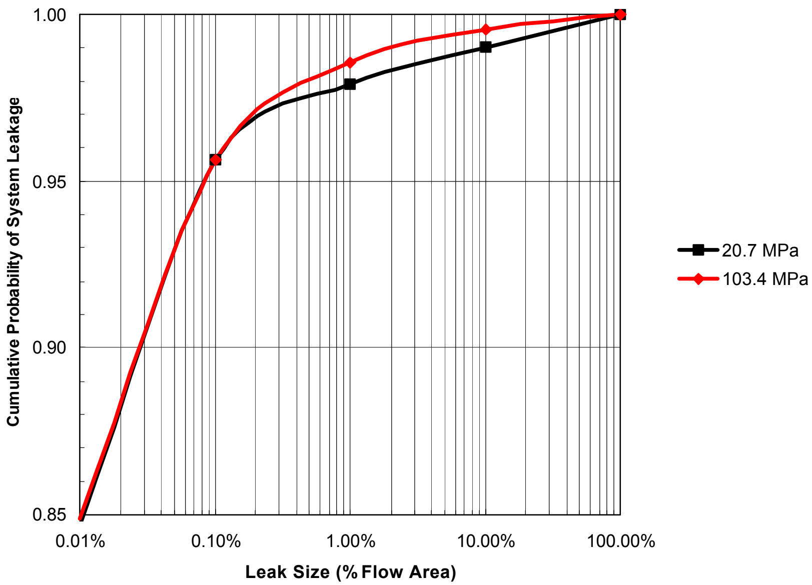
Reference: "Handbook of Parameter Estimation for Probabilistic Risk Assessment," NUREG/CR-6823, U.S. Nuclear Regulatory Commission, Washington, D.C. (2003).

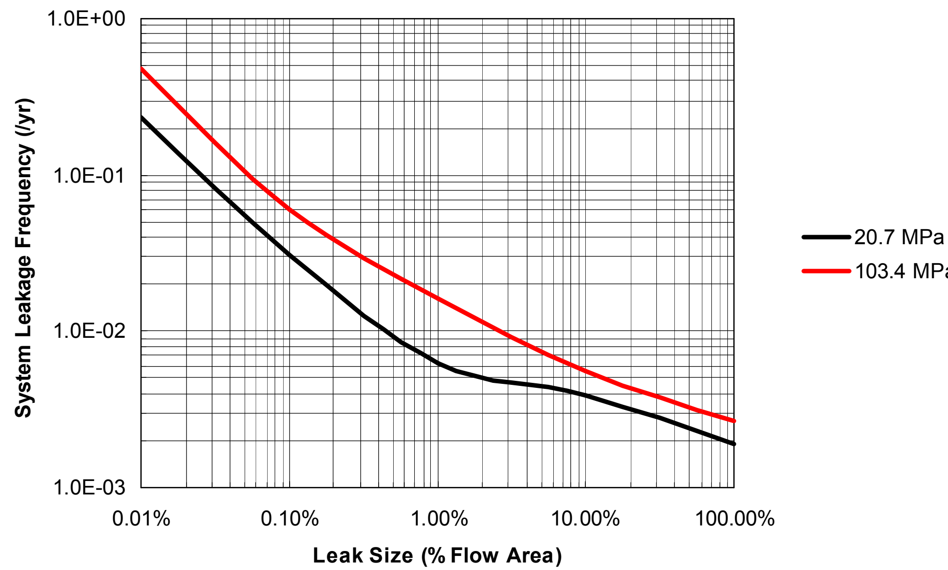
Mean Component Leakage Frequencies from Bayesian Analysis



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:

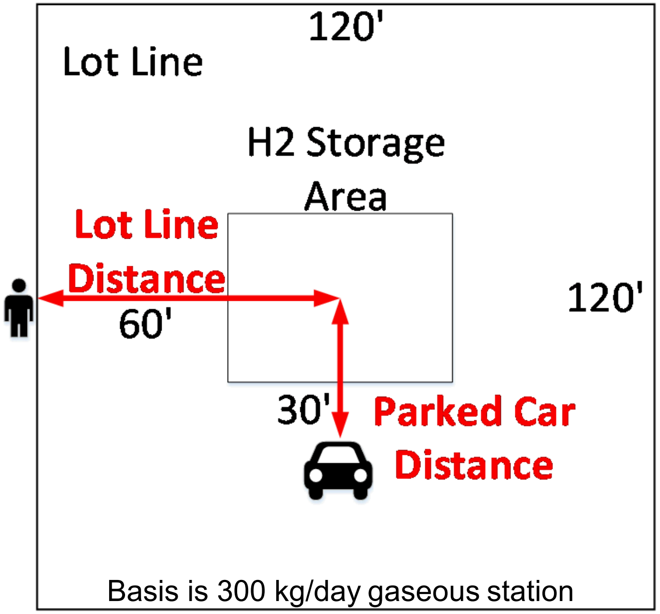
- captures >95% percent of the leaks
- the resulting separation distances protect up to the 3% leak size
- QRA performed to determine if associated risk from leaks greater than this is acceptable

QRA Data, Models, and Assumptions

- Used leak frequencies from Bayesian analysis that incorporates hydrogen-specific data
- Used AVT ignition probabilities
- Used Tsao and Perry Probit function
- Currently only includes random leakage events (common to all facilities)
- No VCEs included in analysis (high momentum jets)
- No volume effects have been incorporated (conservative)
- Surface effects not included (non-conservative)
- Assumes circular leaks (conservative)

Accomplishment: Benchmark Risk Value for Gaseous Hydrogen Station

- Developed draft report which assessed the risk of an H2FIRST reference station using QRA and consequence-only analysis
- Will be integrated into H2FIRST as an appendix (SAND2015-2660R)



Cases	Safety Calculation	Baseline Result
Lot Line Separation Distance	Perform **QRA** on H2First reference station to determine Potential Loss of Life (PLL) metric at 60 ft.	The PLL for this scenario is equal to **2.18E-05** fatalities/system-year.
Parked Vehicle Separation Distance	Perform **consequence** calculation to determine jet flame temperature at 30 ft.	The temperature at 30 ft. is close to **ambient temperature**.

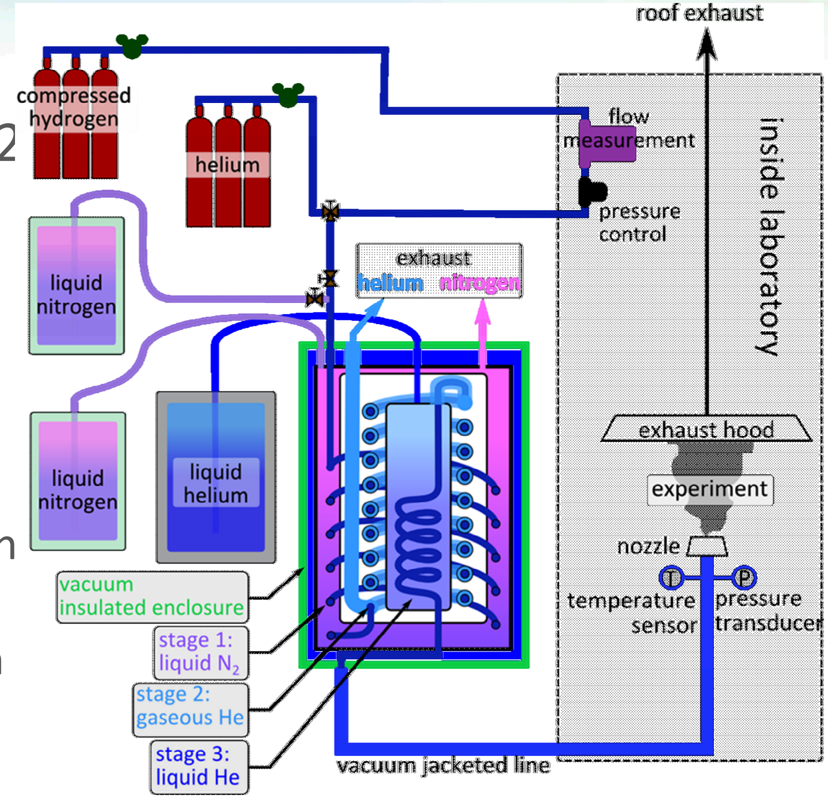
Demonstrating the calculation of benchmark risk values can be used for alternate methods of code compliance.

Approach: Key Barrier – Prescriptive LH2 Separation Distances

- Current bulk distance values
  - Based on historical values
  - Present critical limitation to hydrogen infrastructure growth
- **Science-based Code Improvements** - Ongoing effort by NFPA 2/55 subcommittee to revise based on risk-informed science of LH2 release behavior
- **Alternative Methods for Code Compliance** - In the meantime, this effort is exploring a path forward for short term deviation from separation distances for LH2

Progress: LH2 Informing Science-based Code Revisions

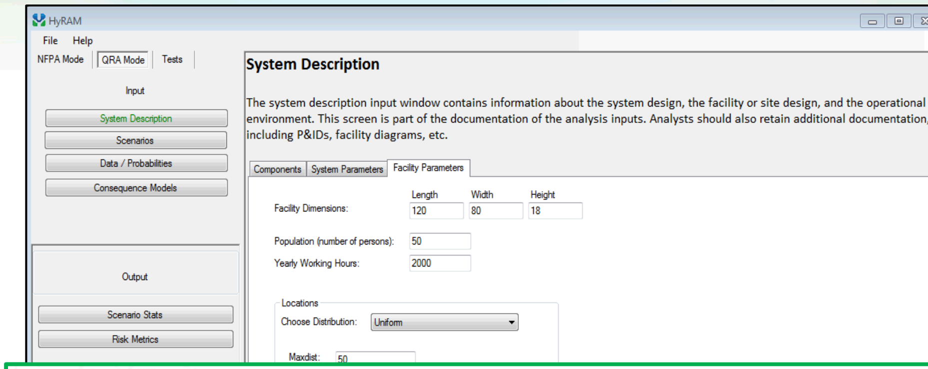
- Goal: Use QRA tools and methods to revise bulk liquid hydrogen system separation distances in NFPA 55/NFPA 2
- Progress:
  - Multi-Party CRADA signed with Bki and Fire Protection Research Foundation to enable industry participation in support of LH2 model validation experimentation efforts
  - Providing technical leadership and hydrogen release behavior models to incorporate current science and technology information to risk-inform code requirements
  - Details given in SCS-010 AMR presentation



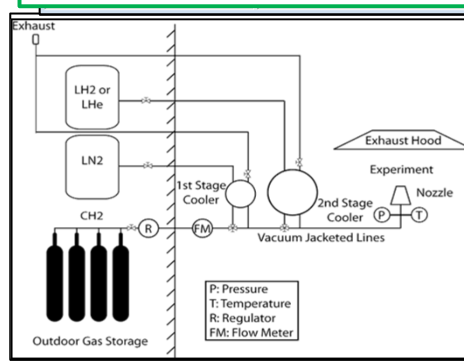
Validated LH2 release model will be used to risk-inform the revised LH2 bulk separation

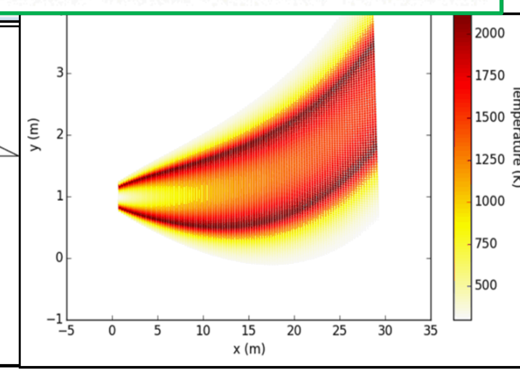
Technology Transfer Activities

- Technology transfer strategies are tied to the accessibility of HyRAM QRA tool kit to other users (AHJs, Station designers, etc.) utilizing alternative means of code compliance
- Refer to AMR SCS-011 presentation



HyRAM
HYDROGEN RISK ASSESSMENT MODELS





Summary

- **Benchmark Risk:**
  - Addresses: Reducing barriers related to lack of technical data for SCS revision
  - By: Identifying research gaps and developing scientific framework for crediting hydrogen system safety features
- **Alternate Means of Code Compliance**
  - Addresses: Education of AHJs,
  - By: Validating and demonstrating alternative methods of code compliance
- **Science-based Code Improvements**
  - Addresses: Reducing barriers related to lack of technical data for SCS revision
  - By: Providing expertise to support science-based code revisions of bulk LH2 separation distances
- **ISO TC 197**
  - Addresses: Harmonization with international codes
  - By: Active technical leadership on working groups revising risk-based methodology