



Information Needed to Support Hydrogen Codes and Standards

Jeffrey LaChance
Sandia National Laboratories

Presented at the
IA HySafe Research Priorities Workshop
BAM Federal Institute for Materials Research and Testing
Berlin, Germany

October 16 and 17, 2012

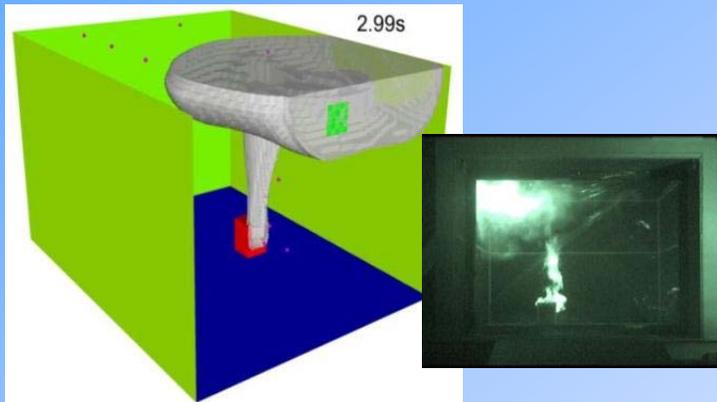


Science-Based, Risk-Informed Codes and Standards

- Challenge is to have a H₂ facility permitting process that is relatively simple and cost-effective but ensures a safe design
 - Many regulators rely on compliance with C&Ss
- Good science and engineering should always be utilized to establish C&S requirements
- Risk information can also be utilized (risk-informed process) when needed
 - Results combined with other considerations to establish minimum code and standard requirements needed for an established risk level
 - Can include defense-in-depth and safety margins in design to address uncertainties

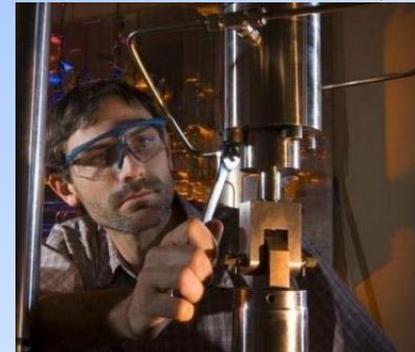
Sandia's R&D Program for Safety, Codes and Standards

Hydrogen behavior



Simulation and experimental validation of release during indoor refueling

H2 effects in materials, components, and systems



Mechanical load-frame used to characterize H2 effects in materials

Technical Reference

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Quantitative Risk Assessments



Quantitative Risk Assessment helps establish requirements for hydrogen installations

C&S development support



Regulations Codes and Standards Advocacy

Safety



Safety is an individual perception - Skydiving may be acceptable to some but not others.



Catastrophic events such as the Hindenburg fire and the hydrogen explosions at Fukushima Dai-ichi nuclear plants can lead to negative attitudes towards hydrogen safety



Risk

- Risk is the quantitative measure of safety - *safety cannot be calculated while risk can*
 - What can go wrong? (Scenarios)
 - How likely is it? (Likelihoods)
 - What are the consequences? (Consequences)

- Risk quantitatively defined as:

Frequency × Consequences

- More specifically:

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



Hydrogen Safety

- The expanded use of hydrogen includes new challenges (e.g., very high pressures) that requires design features and operational requirements to manage the risk to acceptable levels
- Good safety engineering provides means to ensure hydrogen safety
- Quantitative risk assessment (QRA) provides a means to demonstrate the design features and operational requirements are adequate



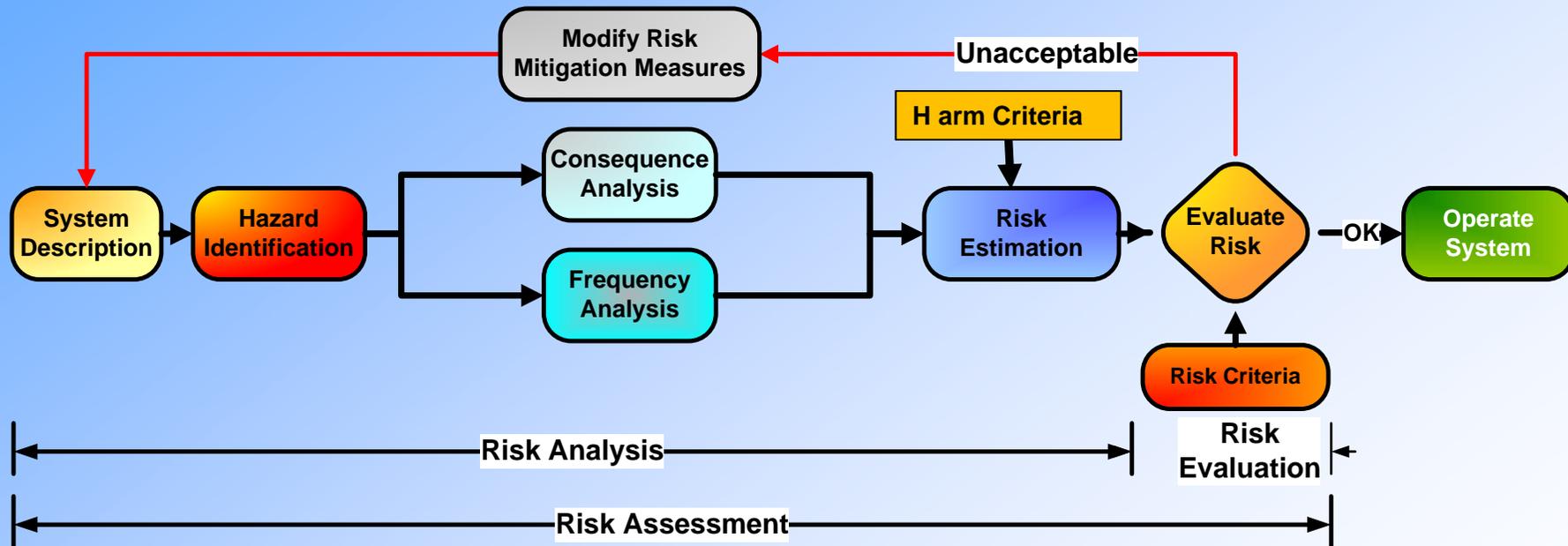
Quantitative Risk Assessment

- QRA models the progression of accidents, and combines the frequencies and consequence of those accidents to estimate risk
- The results of a QRA can provide:
 - Verification that facility meets an accepted risk criteria
 - Identification of important accidents, components, operations contributing to risk
 - Identification and evaluation of risk reduction and control measures
 - Identification of risk management requirements (e.g., maintenance intervals)
- QRA can be used to help design a facility and to generate risk-informed code and standard requirements

QRA Process to Improve Safety

QRA Process Flowchart

Friday, April 28, 2006





Risk Measures

- Human injury or fatality
 - Individual risk – probability that an average unprotected person, at a certain location, is killed or injured due to an accident
 - Societal risk – probability that multiple people within an area are killed or injured due to an accident (typically represented on an FN curve)
- Others
 - Economic loss – typically expressed in terms of loss value (lost income and replacement cost)
 - Environmental damage – can be expressed in terms of time required to recover damage to ecosystem



As Low As Reasonably Practicable (ALARP)

- There is no zero risk situations
- Managing risk to a reasonable level is achievable
- The ALARP principle is that the residual risk should be As Low As Reasonably Practicable – risk can be tolerated if additional risk reducing measures are feasible and their costs are not larger than the benefits
- Tolerable risk represents the level below which an investment will not be made to reduce risk
 - there is no minimum in some versions of ALARP - continuous improvement in safety using best available technology
 - Some versions have target levels
- The minimum risk level that must be obtained, regardless of cost is referred to as the intolerable risk

ALARP Concept – Individual Risk

Unacceptable
Region

Risk must be reduced
regardless of cost unless there
are extraordinary circumstances

ALARP or
Tolerability
Region

Risk tolerable if reduction cost
exceeds improvement achieved

Acceptable
Region

Necessary to maintain assurance
that risk remains at this level
and/or reduced further if
reasonably practical

Negligible Risk



Harm Criteria

A harm criterion is used to translate the consequences of an accident, evaluated from deterministic models, to a probability of harm to people, structures, or components.

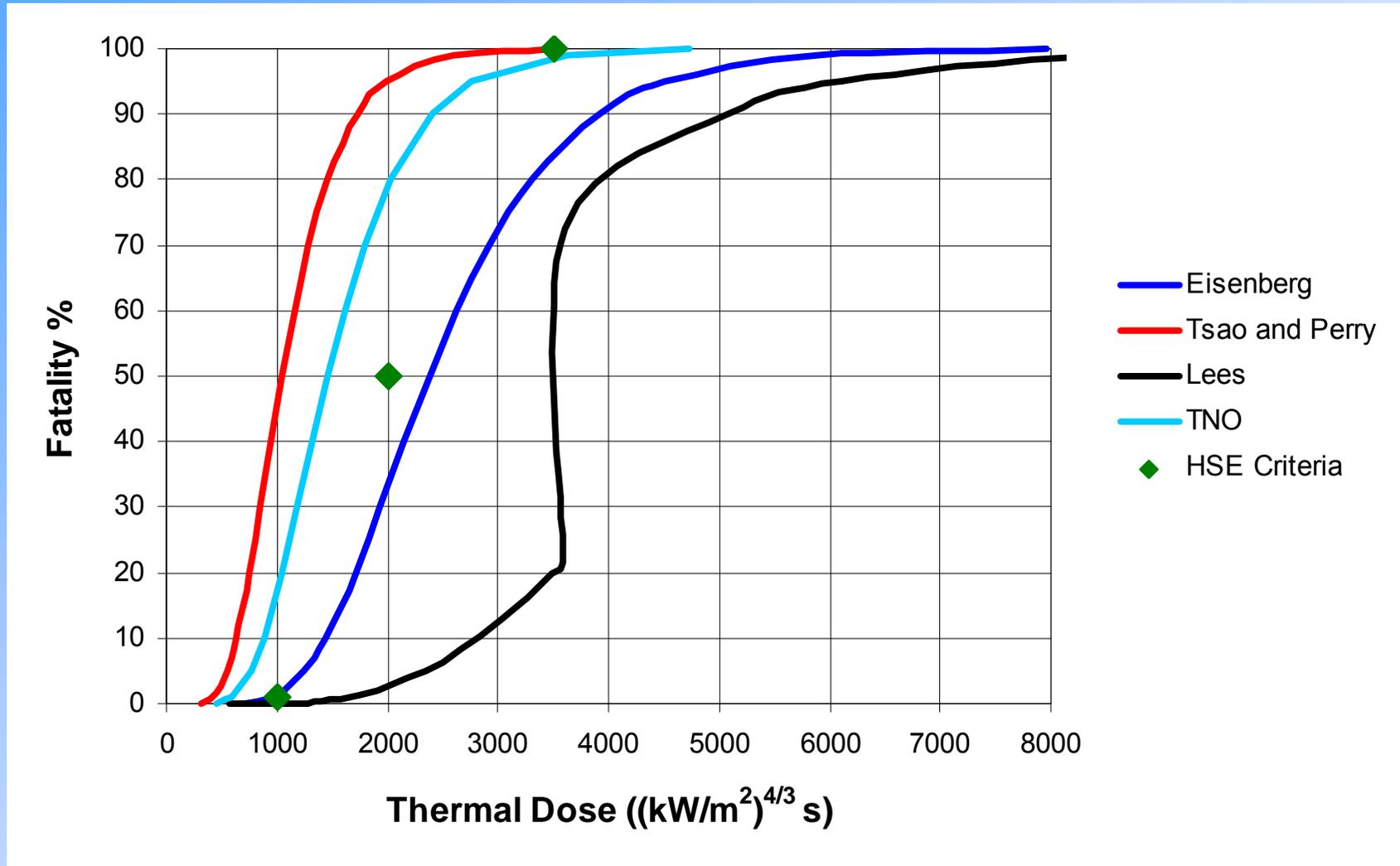
- Harm criteria are required for full range of accidents modeled in QRA
 - Jet fires, flash fires, pool fires, vapor cloud explosions (VCEs), and Boiling Liquid Expanding Vapor Explosion (BLEVE)
- Accident consequences
 - Thermal effects (direct flame contact, high air temperatures, and radiation heat flux)
 - Overpressure effects (direct and indirect)
 - Others (asphyxiation, cryogenic)
- Primary interest is human harm criteria but also need to consider equipment and structures
 - For people, harm criteria can be expressed in terms of injury or fatalities



Types of Harm Criteria

- Single criteria (e.g., thermal radiation)
 - Specified heat flux level and exposure time
 - Specified thermal dose ($I^{4/3}t$)
 - Use of a single criteria is generally used in deterministic evaluations and is not easily utilized in the probabilistic evaluations in QRAs
- Continuous criteria
 - Probit functions – translates hazard measure into probability of injury, fatality, or facility damage
 - Probit functions are particularly useful in QRA since they can provide harm probabilities for the range of accidents included in the risk assessment

Example Probit Functions

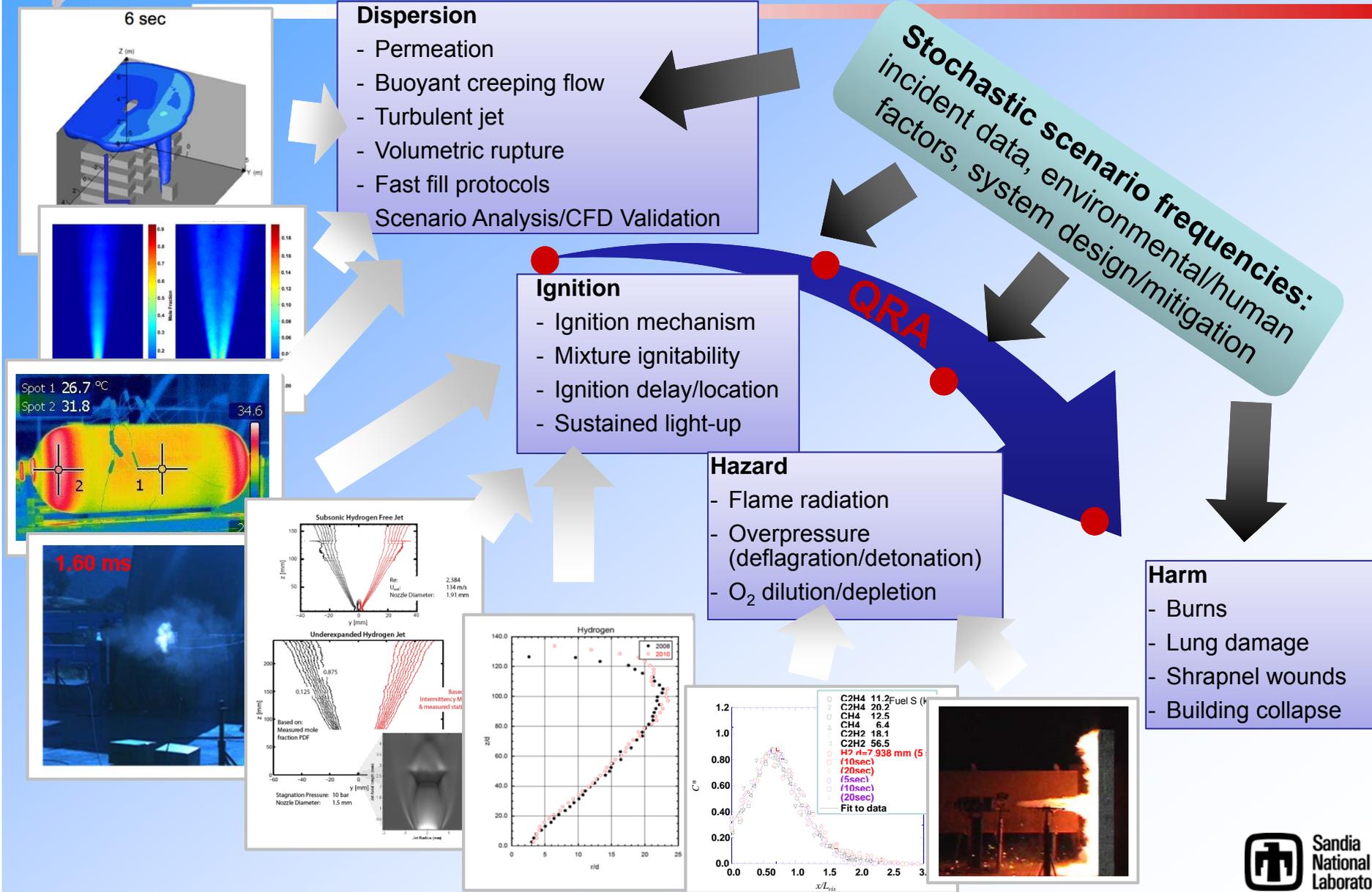




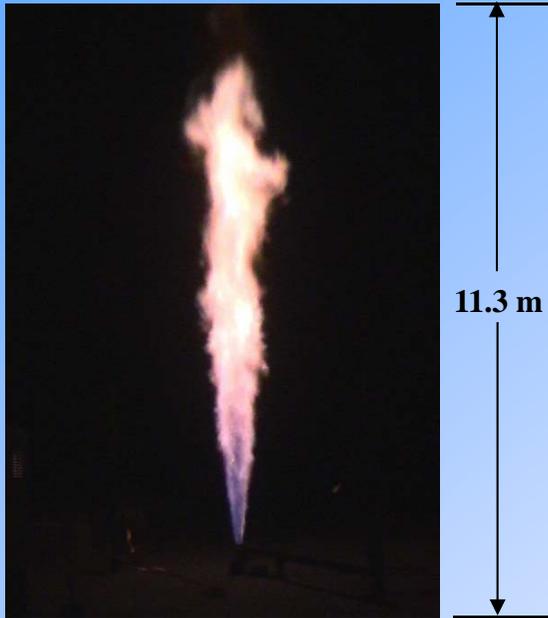
Development of Risk and Harm Criteria

- International collaboration by the International Energy Agency Task 19 – Hydrogen Safety resulted in recommended risk and harm criteria for use in QRAs
- References:
 - A.V. Tchouvelev, J.L. LaChance, and A Engebo, “IEA Task 19 Hydrogen Safety Effort in Developing Uniform Risk Acceptance Criteria for the Hydrogen Infrastructure,” Proceedings of World Hydrogen Energy Conference (WHEC17), Brisbane, Australia, June 15-19, 2008.
 - Jeffrey LaChance, Andrei Tchouvelev, Angunn Engebo, “Development of Uniform Harm Criteria for Use in Quantitative Risk Assessment,” International Journal of Hydrogen Energy, 36 (2011), pgs 2381-2388.

Information Needed to Quantify QRAs



Understanding and Quantifying the Consequences of Unintended Releases of H₂ Needed for QRA



Nighttime photograph of 413 bar (6000 psig) large-scale H₂ jet-flame test ($d_j = 5.08\text{mm}$, $L_{\text{vis}} = 10.6\text{ m}$) from Sandia/SRI tests.

- Objects exposed to a hydrogen plume can encounter
 - Heating from radiation (ignited jet)
 - Flame impingement (ignited jet)
 - Combustible cloud contact (unignited jet)
- Each of these items impacts the development and determination of risk
- Experimental measurements
 - Flame shape and flame impingement distances for different flow rates
 - Hydrogen flame radiation values
 - Lean ignition limit for hydrogen/air mixtures
- Computational models with validation
 - Jet flame radiation model
 - Unignited jet flammability limit contour model
 - Predictions outside the range of available data

Ignition Probabilities

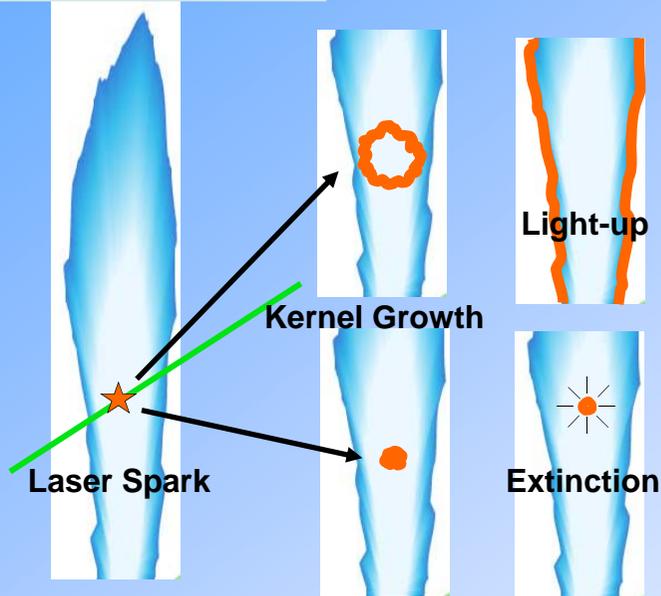
- Values used in SNL QRAs
- ISO QRA used probability of 0.04 for all leak sizes
- Probabilities proposed by HYSAFE

Hydrogen Release Rate (kg/s)	Immediate Ignition Probability	Delayed Ignition Probability	Total Ignition Probability
<0.125	0.008	0.004	0.012
0.125 – 6.25	0.053	0.027	0.08
>6.25	0.23	0.12	0.45

Hydrogen Release Rate (kg/s)	Immediate Ignition Probability
0.01- 0.1	0.001
0.1-1	0.001 + 0.001 when P>100 bar
1-10	0.01 + 0.01 when P>100 bar
>10	0.1 + 0.01 or 0.02

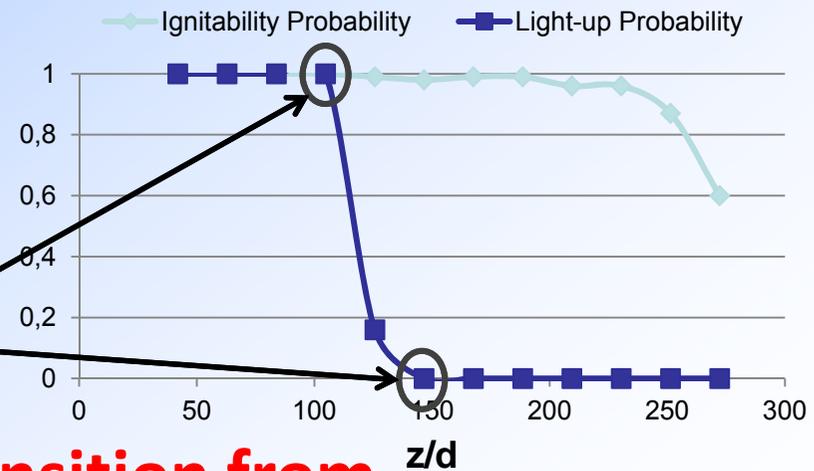
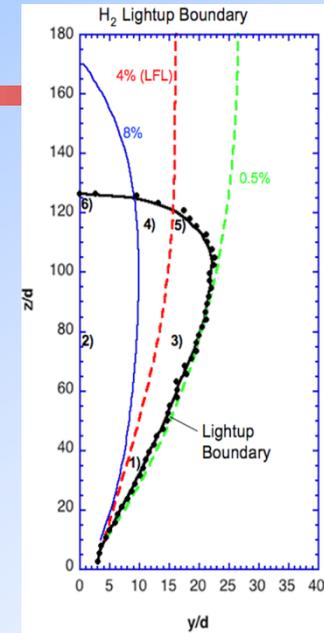
Need a Probabilistic Hydrogen Ignition Model for QRA

1.91 mm tube (unchoked)
100 lit/min flow rate



High-speed schlieren imaging

Schefer et al., 2011



What mechanisms drive the transition from H₂ ignition to sustained flame light-up?



Data Needed for QRA

- Initiating Event Frequencies
- Basic Event Probabilities
 - Hardware
 - component reliability (fail to start/run/operate/etc.)
 - component unavailability (due to test or maintenance)
 - Conditional probabilities (e.g., ignition given a leak)
 - Common Cause Failures
 - Human Errors



Information Required

- Initiating Event Frequencies (time-dependent failures):
 - Number of events/total operation time (e.g., number of leaks from valves/number of valve operating]
- Component Failure on Demand:
 - Number of failures/number of demands (e.g., number of isolation valve failures to close/number of isolation valve demands to close)
- Maintenance Unavailability:
 - Time out for maintenance/total facility operation time (e.g., time hydrogen detector out of service/operation time)



Limited Data is Being Collected

- Data bases such as HIAD and DOE H2Incidents provide goods insights and suggestions for improvements, but not sufficient for QRA
- Some H2 equipment suppliers collect data to improve their products
 - Utilized by Sandia in QRAs
- No mechanism (e.g., regulator requirements) for collecting data – exception is DOE Technology Validation program for refueling facilities (collected by NREL)
 - Focused on operational and safety aspects but does not all have data needed for QRA



Data Available on NREL Website

- Leak frequency data
 - Leakage event descriptions including severity
 - Component where leakage occurs
 - Operation time for major components
 - Missing data – number of valves, joints, etc. in facilities
 - Severity categorization is crude and would require review of event description to put into useful leak sizes
- Other safety incidents/initiating events (e.g., human errors resulting in drive aways)



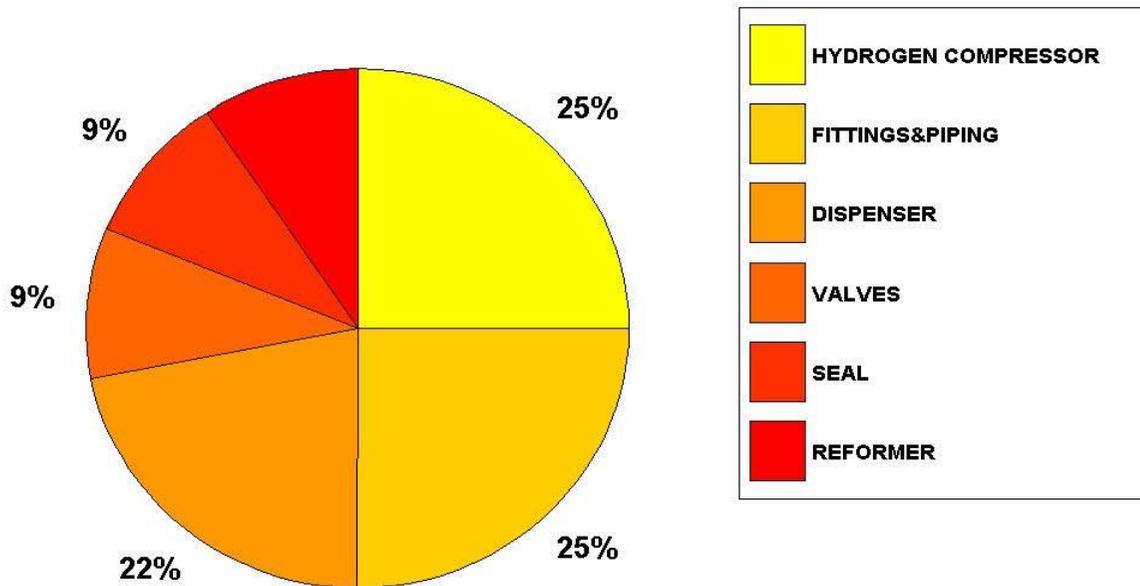
Data Available on NREL Website

- Component failure on demand
 - Appears to include subsystem and some specific equipment failures
 - Includes number of refuelings
- Maintenance Unavailability
 - Number of scheduled and unscheduled maintenance hours for system, **but not by component**
 - Facility operation times
- Conditional probability of ignition
 - Number of leakage events that were ignited
 - Number of leakage events and severity

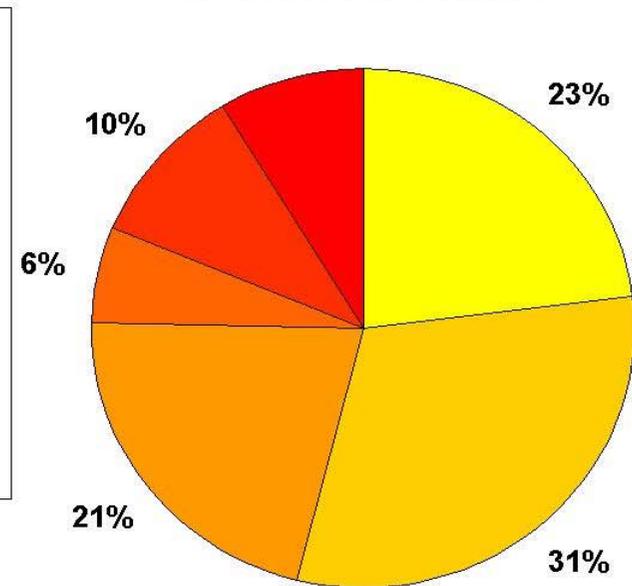
Leakage Data on NREL Website

Hydrogen Leaks By Equipment Category: Infrastructure

By Number of Events
Total Number of Events = 32
100% were unscheduled



By Labor Hours
Total Hours = 335
100% were unscheduled



What size are the leaks and what is the operating time for each component type?

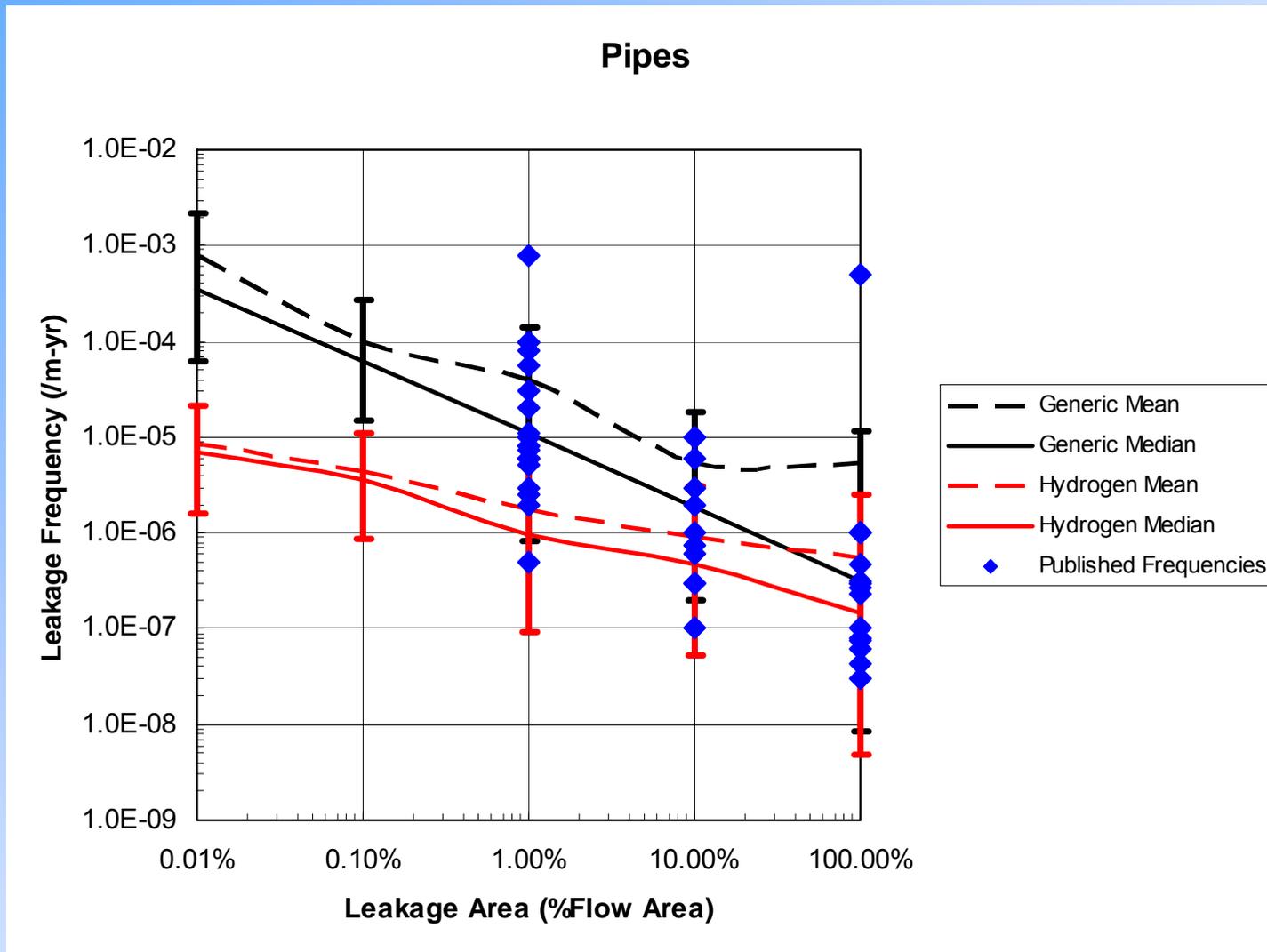


Bayesian Methods Employed to Generate H₂ Failure Estimates

- Two motivations for using Bayesian techniques
 - Generate probability distributions (classical methods generally only produce uncertainty intervals, not pdf's)
 - Compensate for sparse data (e.g., no failures)
- In effect, Bayesian techniques combine an initial estimate (prior) with plant-specific data (likelihood function) to produce a final estimate (posterior)
- However, Bayesian techniques rely on (and incorporate) subjective judgment
 - different options for choice of prior distribution (i.e., the starting point in a Bayesian calculation)

Bayesian Results - Pipes

No hydrogen failures in very large operating history.





Common Cause Failures (CCFs)

- Conditions which may result in failure of more than one component, subsystem, or system
- Common cause failures are important since they:
 - Defeats redundancy and/or diversity
 - Data suggest high probability of occurrence relative to multiple independent failures



Human Error is a Significant Contributor to Risk

➔	Accidents at Sea	90%
➔	Chemical Industry	80-90%
➔	Airline Industry	60-87%
➔	Commercial Nuclear Industry	65%

Regardless of the domain, there seems to be general agreement that 60-90% of all system failures could be attributed to erroneous human actions.

Major accidents - hardware problems or other “environmental” factors + multiple human errors.



QRA Quality Aspects

- QRA Standard
 - Complimentary to facility and component design standards
- QRA Procedures
 - Several Procedure guides exist (e.g., TNO books, others) and can be adapted for hydrogen QRAs
- QRA tool box (e.g., KIT toolbox)
- Peer Review Process



Risk Assessment Tools for Supporting the Permitting Process

- Development of comprehensive QRA models are required to support development of codes and standards
 - Seismic, and other external hazards need to be considered
- QRA toolkit can also be used to:
 - Help facility designers in complying with codes and standards, developing mitigation strategies, provide a basis for exemptions to requirements
 - Educate authorities on possible hydrogen accidents and consequences
- Important features of QRA toolkit include:
 - Simple but realistic models for all possible accidents
 - Accepted data values for frequency of accidents, failure of mitigating equipment, and phenomenological events
 - Propagation of parameter uncertainty and performance of sensitivity studies to address assumptions and model uncertainty
 - Choice of risk criteria for establishing adequacy of a design



Summary

QRA 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.



Summary

QRA Research Needs

- Need to develop methods and data for modeling human errors
- Need framework for addressing uncertainty in risk-informed decision making
- Need to address external hazards
- Defense-in-depth concepts should be incorporated in C&S
- QRA quality processes should be established



Backup Slides

10/19/2012



Sandia's Efforts in Hydrogen Safety

- Work performed under U.S. DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program, *Multi-Year Research, Development and Demonstration Plan*
 - Hydrogen Safety, Codes & Standard R&D
- Sandia National Laboratories is developing the scientific basis for assessing credible safety scenarios and providing the technical data for use in the development of codes and standards
 - Includes experimentation and modeling to understand behavior of hydrogen for different release scenarios
 - Use of Quantitative Risk Assessment (QRA) methods to help establish requirements in codes and standards



QRA Inputs

- Requires definition of acceptable risk guidelines
- Requires identification of possible hazards
- Requires models for possible accidents
- Requires data analysis for quantification of QRA models
- Requires deterministic evaluation of hydrogen behavior
- Harm criteria to translate hazard information into consequence measures



Risk Acceptance Criteria

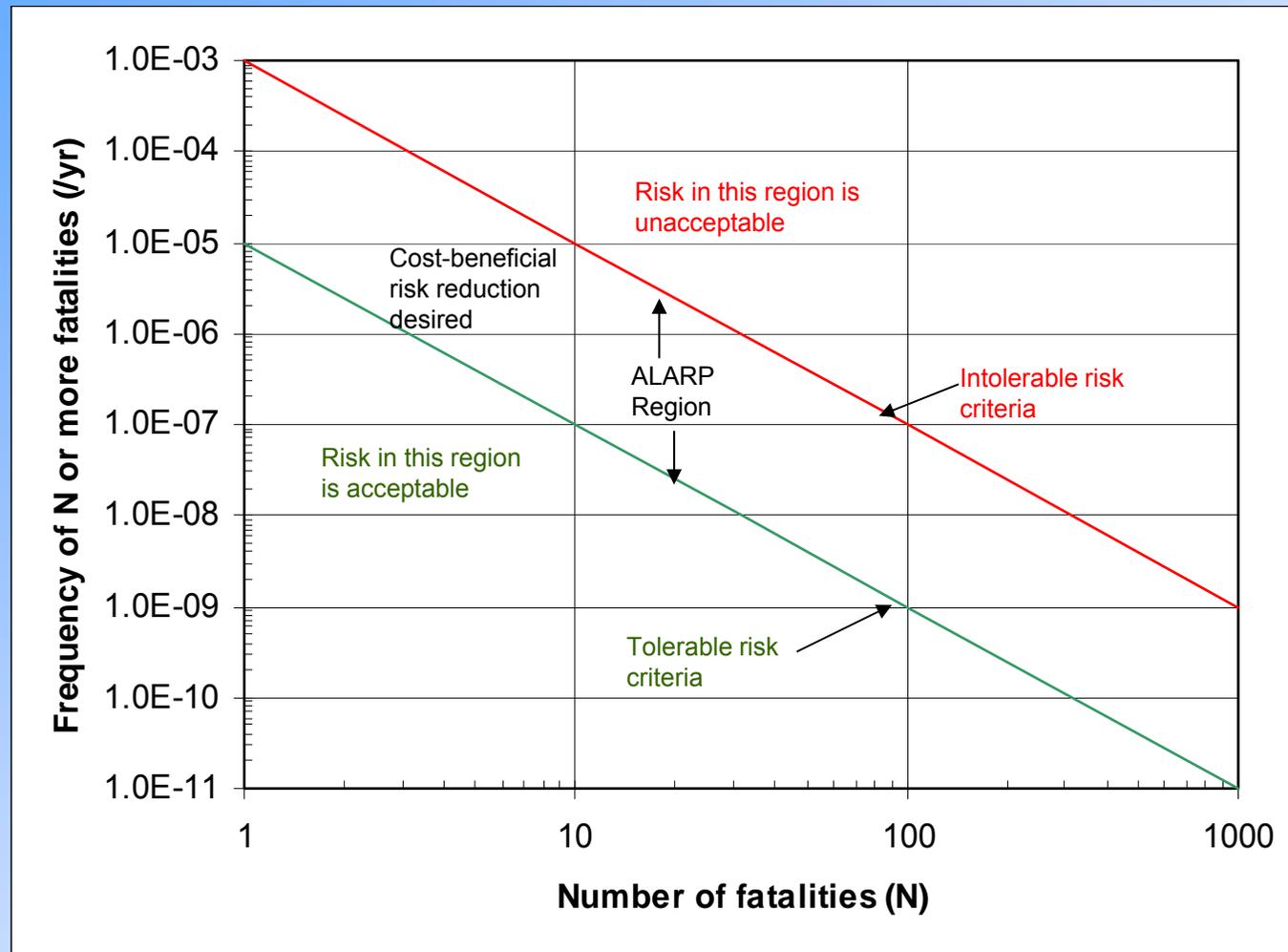
- Uniform risk acceptance criteria is required for development of risk-informed codes and standards
- Options considered for selecting risk criteria:
 - Based on statistics from existing stations (gasoline and CNG)
 - limited data available
 - data includes accidents other than accidental releases
 - NFPA data for gasoline stations in U.S. suggests frequency of deaths and injuries are $\sim 2 \times 10^{-5}/\text{yr}$ and $\sim 3 \times 10^{-4}/\text{yr}$, respectively
 - Based on estimated risk for existing stations
 - limited analyses are available
 - differences in facilities affects comparison of data
 - Comparing with general risk in society – hydrogen should not increase the general risk level in society
 - Risk of death $\sim 2-4 \times 10^{-4}/\text{yr}$; risk of injury $\sim 0.09/\text{yr}$ in U.S.
 - Fraction of total risk from just from fires ($1.3 \times 10^{-5}/\text{yr}$ in the U.S.) and explosions ($6 \times 10^{-7}/\text{yr}$ in the U.S.)



Risk Exposed Persons

- Public – people located outside the facility boundary
 - People living and working near the facility
 - People visiting or traveling near the facility
- Customers – people using the facility
 - Limited exposure period
- Facility operators – personnel involved in operation, inspection, and maintenance of the facility
 - Generally assumed these people accept higher risk levels than for customers and outside public

ALARP Concept – FN Curve





Suggested Guidance on Public Risk Criteria

- Individual Risk – ALARP with following criteria:
 - Unacceptable risk level - 1×10^{-5} /yr
 - Basis – Comparative risk to gasoline stations, 10% of risk to society from all other accidents, representative value used by most countries
 - Acceptable risk level – 1×10^{-7} /yr
 - Basis – Representative of most countries
- Societal Risk – Adopt EIHP ALARP FN curve
 - Basis – risk aversion factor of 2 and with a pivot point for 100 fatalities of 1×10^{-5} /yr for unacceptable risk curve and 1×10^{-7} /yr for acceptable risk curve
- Customer and Worker risk – 1×10^{-4} /yr
 - Basis – Order of magnitude higher than the individual unacceptable risk value



Example Criteria – Heat Flux Levels

- Example human harm criteria (assumes exposed skin):
 - 1.6 kW/m² – no harm for long exposures
 - 4 to 5 kW/m² - pain for 20 second exposure
 - 9.5 kW/m² -Second degree burns within 20 seconds
 - 12.5 to 15 kW/m² - 1% lethality in 1 minute
 - 25 kW/m² - 100% lethality in 1 minute, injury within 10 seconds
 - 35 to 37.5 kW/m² - 1% lethality in 10 seconds



Suggested Guidance on Harm Criteria

- Direct flame contact
 - Assume a fatality if located within plume (2 X flame length)
- Radiation heat flux
 - Use of thermal dose criteria may be preferable to radiation heat flux criteria (useful for deterministic evaluations but not for QRA)
 - Probit functions are a better option since they give probability as function of dose (no hydrogen-specific probit function available)
 - Use of both the Tsao and Perry and Eisenberg probit functions are recommended in order to evaluate the uncertainty in the harm predictions for hydrogen fires
- Overpressure effects
 - Indirect effects (structural collapse, missiles, body translation) are more important than direct health effects (lung damage)
 - Probit functions are a better option than the use of selected overpressure criteria
 - TNO probits are recommended since they provide consistent framework for evaluating overpressure effects



Some Issues to Consider

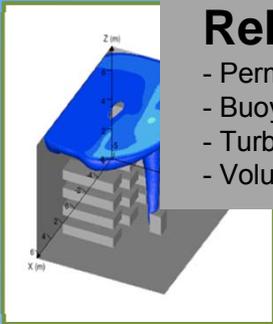
- Use risk “Guideline” versus “Criteria”
 - Conveys concept that we are providing guidance
 - In risk-informed space, more than risk is considered
 - Large uncertainty in risk evaluations
 - Should not make decisions based on comparison to hard risk criteria difficult
- Need guidance on uncertainty assessments and impact on decision making
 - Evaluate epistemic (modeling) uncertainties
 - Do we use the mean, median, or a percentile when comparing to guideline?
- Need guidance on cost-benefit evaluation in ALARP
 - What guidelines should be used?

Risk-Informed Approach

Use validated simulations, field data and expert input to determine risk through quantitative risk assessment.

Release Probability

- Permeation
- Buoyant creeping flow
- Turbulent jet
- Volumetric rupture

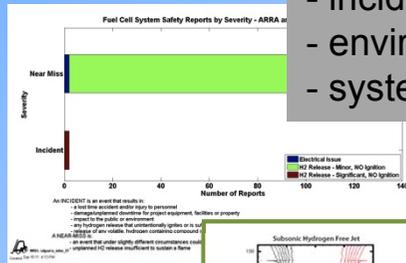


Informed Input

Code development groups, industry, regulators and code enforcers

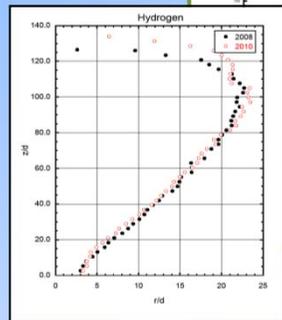
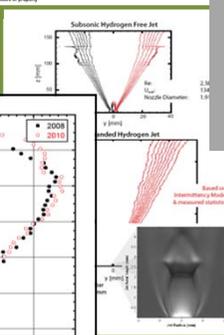
Field Data Input

- incident data,
- environmental/human factors,
- system design/mitigation



Ignition Probability

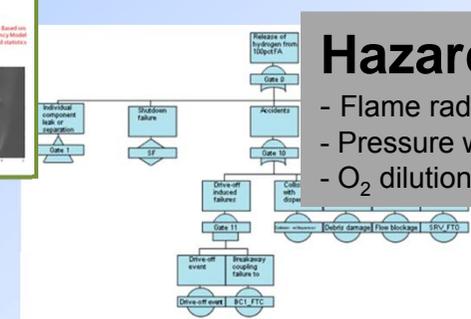
- Ignition mechanism
- Mixture ignitibility
- Ignition delay/location
- Sustained light-up



QRA

Hazard Probability

- Flame radiation
- Pressure wave (deflagration/detonation)
- O₂ dilution/depletion



Harm Probability

- Burns
- Lung damage
- Shrapnel wounds
- Building collapse



Bayes Theorem

$$P(\theta = \theta_i | \varepsilon) = \frac{P(\varepsilon | \theta = \theta_i)P(\theta = \theta_i)}{P(\varepsilon)} = \frac{P(\varepsilon | \theta = \theta_i)P(\theta = \theta_i)}{\sum_i P(\varepsilon | \theta = \theta_i)P(\theta = \theta_i)}$$

Where:

- $P(\varepsilon | \theta = \theta_i)$ - The conditional probability that the value ε will be observed for the random variable X in a given trial, *assuming the value θ_i for the parameter θ* .
- $P(\theta = \theta_i)$ - The prior – prior to observing the value ε for X ; can also be stated as “prior to obtaining the evidence” – probability that the value of θ is equal to θ_i .
- $P(\varepsilon)$ - The total probability that the value ε will be observed for the random variable X , *summed over all possible values θ_i for the parameter θ* .
- $P(\theta = \theta_i | \varepsilon)$ - The posterior – after observation of the value ε for X – probability that the value of θ is equal to θ_i .



Types of Prior Distributions

- **Non-informative prior (Jeffrey's Prior)**
 - Conveys little prior belief or knowledge – allows data to speak for itself. No informed consensus on what the true value might be (0.5).
- **Informative prior**
 - Use generic data as prior belief about value and uncertainty
- **Constrained non-informative prior**
 - This prior is a compromise between an informative prior and the Jeffreys non-informative prior. The mean of the constrained non-informative prior uses prior belief, but the dispersion is defined to correspond to little information.

Example

Refueling Nozzle Break Away Fails to Close After Drive Away (0 failures in 31 events)

Method	Prior Mean	Posterior Parameters		Point Estimate (MLE or Posterior Mean)	5% percentile	95% percentile
Frequentist	NA	NA	NA	0	0	9.50E-02
Bayes with Noninformative Prior beta (0.5,0.5)	0.5	0.5	31.5	1.56E-02	6.19E-05	5.75E-02
Bayes with Informative Prior beta (0.5,5E3)	1.00E-04	0.5	5031	9.94E-05	3.88E-07	3.82E-04
Bayes with Constrained Noninformative Prior beta (0.5,5031)	9.94E-05	0.5	5062	9.88E-05	3.85E-07	3.79E-04

10/19/2012



Failure Probability Models

- Demand Failures

- Binomial: $\text{prob}(r \text{ failures in } n \text{ demands}) = \{n!/[r!(n-r)!]\} * p^r(1-p)^{n-r}$

- $\text{prob}(1 \text{ failure} | 1 \text{ demand}) = p = Q_d$

- Failures in Time

- Poisson: $\text{prob}(r \text{ failures in time } t) = (1/r!) e^{-\lambda t}(\lambda t)^r$

- $\text{prob}(r > 0, \text{ in time } t) = 1 - e^{-\lambda t} \approx \lambda t \text{ (for } \lambda t \ll 1)$



Permitting Process

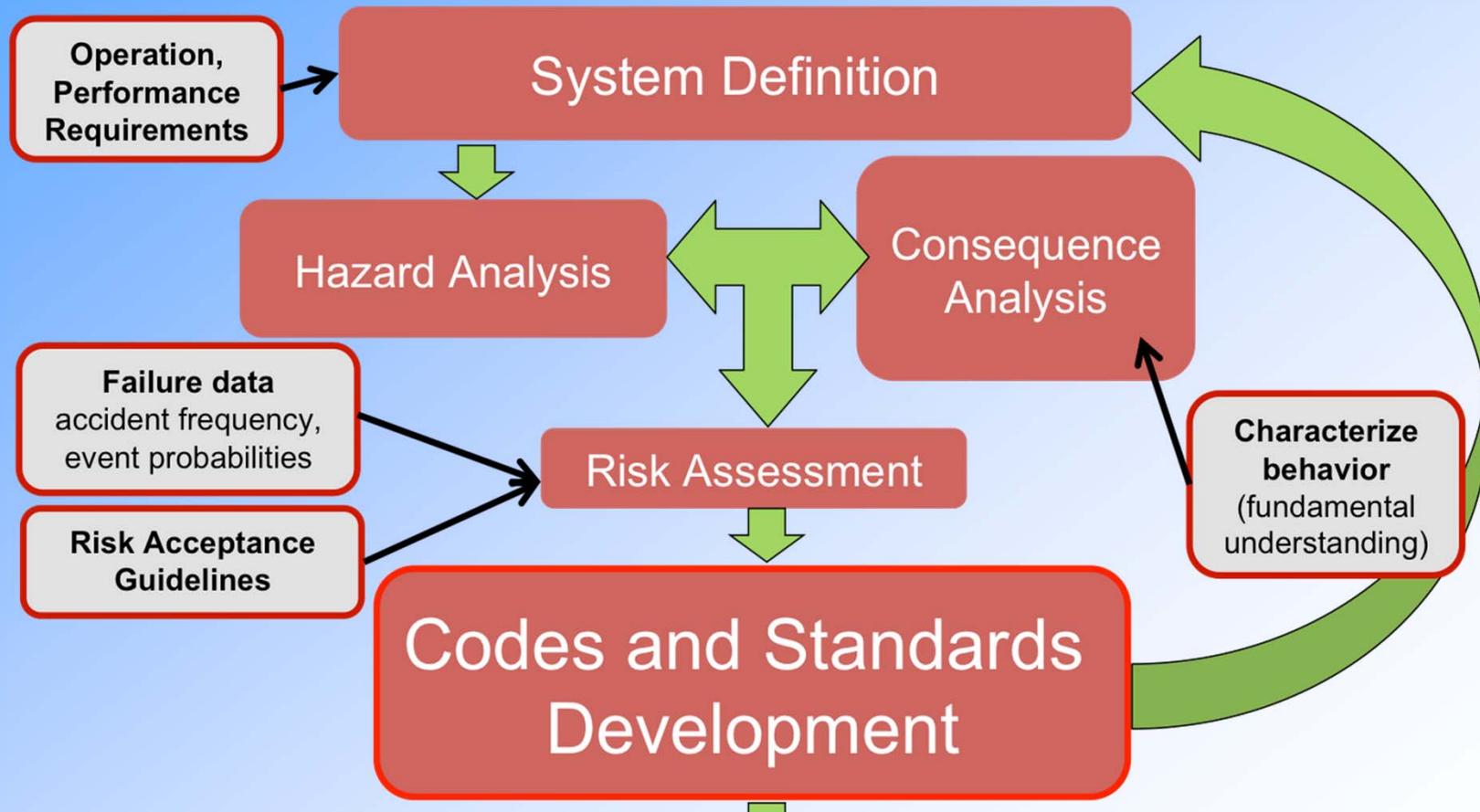
- Purpose is to demonstrate that facility meets established safety requirements
- Many permitting authorities rely on compliance with codes and standards
- Current codes and standards specify safety features, material requirements, separation distances, operational requirements, risk management plans, etc.
- Compliance with codes and standards is accepted as evidence of a safe design



Risk-Informed Codes and Standards

- Use of a risk-informed process is one way to establish the requirements necessary to ensure public safety
 - Endorsed by Fire Protection Research Foundation (“Guidance Document for Incorporating Risk Concepts into NFPA Codes & Standards”)
 - Comprehensive QRA used to identify and quantify scenarios leading to hydrogen release and ignition
 - Accident prevention and mitigation requirements identified based on QRA
 - Results combined with other considerations to establish minimum code and standard requirements needed for an established risk level

QRA Process





Possible Further Work

- Have not yet addressed:
 - Convective heat transfer
 - Asphyxiation (requires large mole fraction of hydrogen)
 - Cryogenic effects (oxygen enrichment and pressurization/explosion due to rapid vaporization)
- Need to look for additional methods
 - E.g., skin effect models (skin damage as function of temperature)



The Problem

- There is little hydrogen-specific data that is available for use in QRA
- Probably will never be enough to utilize traditional statistical methods

So what data do you do?



A Solution

- Use Bayes Theorem to combine multiple sources of generic data
 - Can give equal weight to all sources
 - Can give variable weight to sources
- Update results (prior) as new information (i.e., hydrogen-specific data) becomes available (posterior)
- Provides uncertainty distributions
- Use most applicable data from available sources to fill in where you have no hydrogen-specific data



Common Cause Failure Mechanisms

- Environment
 - Temperature
 - Corrosive environment
- Design deficiency
- Manufacturing error
- Test or Maintenance error
- Operational error



Human Reliability Analysis

- Starts with the basic premise that the humans are, in effect, part of the system (i.e., “human-machine systems”).
- Identifies and quantifies the ways in which human actions contribute to the initiation, propagation, or termination of accident sequences.
- HRA has gathered information from the behavioral sciences to provide a mechanism for estimating human failure probabilities



Categories Of Human Error

- Errors can occur throughout the accident sequence
 - Pre-initiator errors (latent errors that may occur during test or maintenance)
 - Failure to restore
 - Miscalibration
 - Often captured in equipment failure data
 - For HRA focus is on equipment being left unavailable or not working exactly right
 - As a contribution or cause to initiating events
 - Usually implicitly included in data used to quantify initiating event frequencies



Categories Of Human Error (cont.)

- Errors can occur throughout the accident sequence (cont.)
 - Post-initiator errors
 - Operation of components from central control station or locally
 - Operation of components that have failed to operate automatically
 - “Sequence level” errors modeled in the event trees (e.g., failure to isolate hydrogen source given leak detection in accordance with procedure)
 - Recovery actions (consideration of actions that may be taken to recover from a fault depending upon actions required and amount of time available)
 - Self-Recovery of human failures



Types Of Human Error

- Generally, two types of human errors are defined:
 - Errors of omission (EEO) -- Failure to perform a required action or step, e.g., failure to monitor makeup tank level
 - Errors of commission (EOC) -- Action performed incorrectly or wrong action performed, e.g., opening the wrong valve, turning off safety injection
- Traditionally only the first type is modeled due to uncertainty in being able to identify errors of commission, and lack of modeling and quantification methods to address such errors

Development/Validation of Deterministic Models to Complement/Support QRA

SNL R&D for H₂ Safety, Codes & Standards

Develop Science Basis for H₂ SCS

Quantify H₂ relevant failure modes & scenario variables

Hydrogen effects in structural materials

Experiments & modeling to describe release/ignition behavior

- Choked flow dispersion model development
- Qualitative high-speed flame ignition imaging
- Jet flame light-up engineering model development

Validated simulations & engineering for consequence modeling

- Large-scale jet flame radiation analysis

Impact & Harmonize H₂ SCS Development

Consequence & Risk:

Participation in:
HIPOC, ISO, NFPA, ICC

International Engagement:

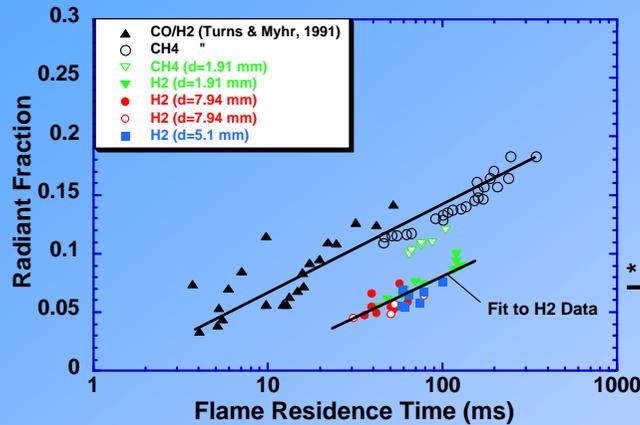
Participation in:
ISO, IEA, IPHE, GTR, H2CAN



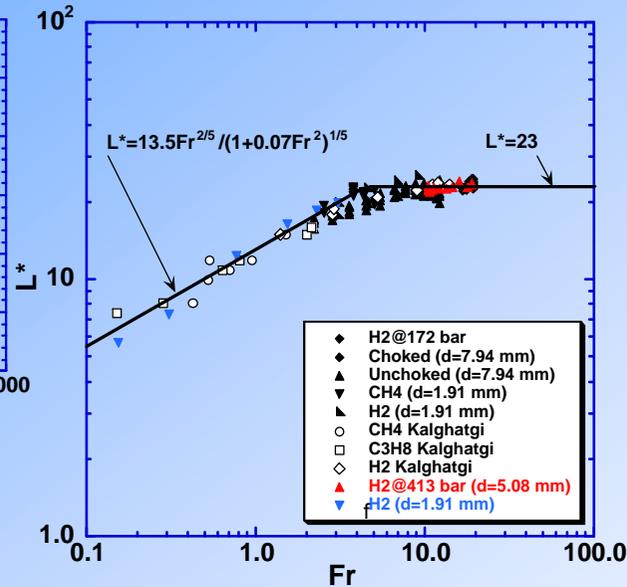
Standards advocacy ensures transfer of science-based H₂ SCS knowledge to code development committees.

Example - SNL developed an engineering model for the radiation heat flux and flame length for H₂ jet flames based on flame data correlations.

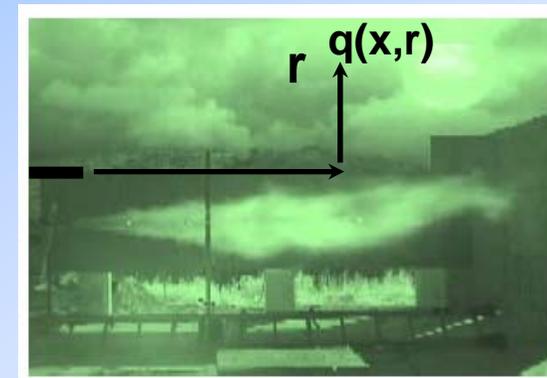
Radiant Fraction (X_{rad})



Visible Flame Length



- SRI Test Facility
- Baseline circular nozzle, 7.9375 mm (5/16 in)

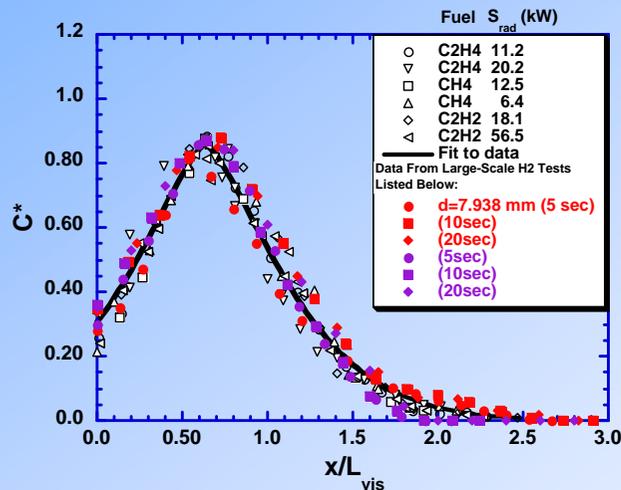


Horizontal Flame

3.6 - 4.3 m long, 0.6 - 1m wide

$$q(x,r) = \frac{C^* X_{rad} m_{fuel} \Delta H_c}{r^2}$$

Radiant Power



- H₂ jet-flame radiation model verified at source pressures of (172 bar (2500 psig), 413 bar (6000 psig)).

- (1) Houf & Schefer, "Predicting Radiative Heat Fluxes and Flammability Envelopes from Unintended Releases of Hydrogen," Int. Jour. Hydrogen Energy, Vol. 32, pp. 136-151, 2007.
- (2) Schefer, Houf, Bourne, Colton, "Spatial and Radiative Properties of an Open-Flame Hydrogen Plume," Vol. 31, pp. 1332-1340, 2006.
- (3) Schefer, Houf, William Bourne, Colton, "Characterization of High-Pressure Underexpanded Hydrogen-Jet Flames," Vol. 32, pp. 2081-2093, 2007.

Validation is important - The model is able to reproduce flame lengths measured in the Sandia/SRI hydrogen jet flame experiments.

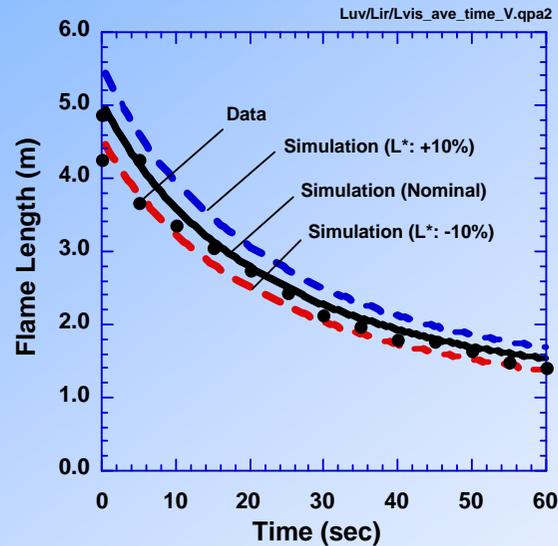
SRI Test Facility

Baseline circular nozzle, 7.9375 mm (5/16 in)



Horizontal Flame

3.6 - 4.3 m long, 0.6 - 1m wide

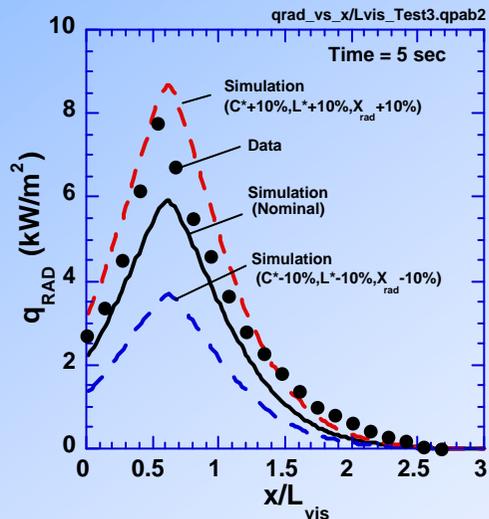


Simulation of SRI/Sandia
Jet Flame Experiment

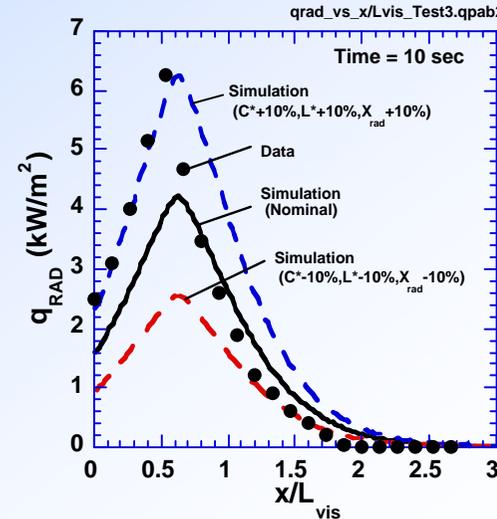
Tank Pressure = 172 bar
(2500 psia)

Tank Volume = 0.098 m³

Comparison of Simulations with Heat Flux Data

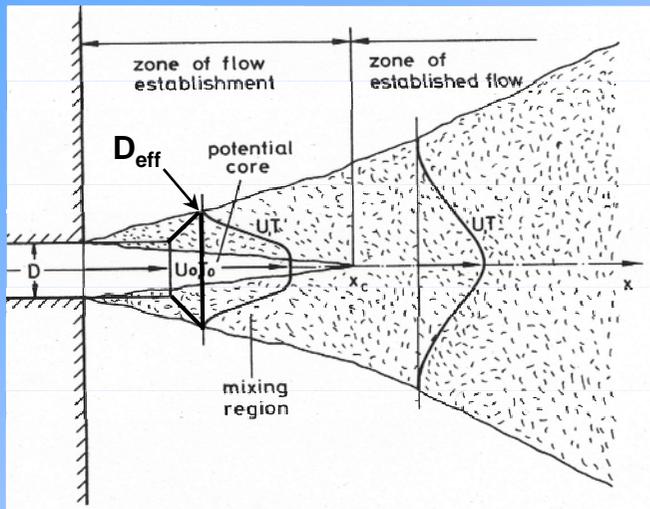


Comparison of Simulations with Heat Flux Data



SNL has developed a model to predict flammability envelopes from high-momentum unignited H₂ jets.

Schematic of High Momentum H₂ Jet Exiting to Air



- Effective diameter nozzle expansion for underexpanded jet

$$D_{\text{eff}} = (\rho_{\text{exit}} V_{\text{exit}} / \rho_{\text{eff}} V_{\text{eff}}) D$$

$$V_{\text{eff}} = V_{\text{exit}} + (P_{\text{exit}} - P_{\text{amb}}) / \rho_{\text{exit}} V_{\text{exit}}$$

- Entrainment law for turbulent jets

$$C_{\text{cl}}(x) = KD / (X + X_0) (\rho_{\text{amb}} / \rho_{\text{H}_2})^{1/2}$$

$$C(x, r) = C_{\text{cl}}(x) \exp(-K_c (r / (x + x_0))^2)$$

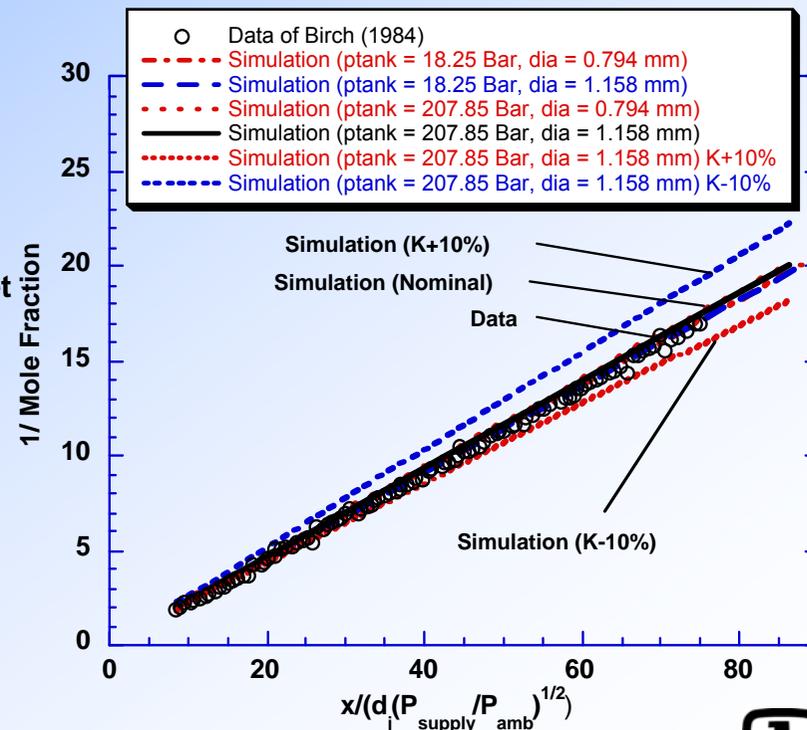
$$K_c = 57$$

$$K = 5.40$$

$$D = \text{Diameter}$$

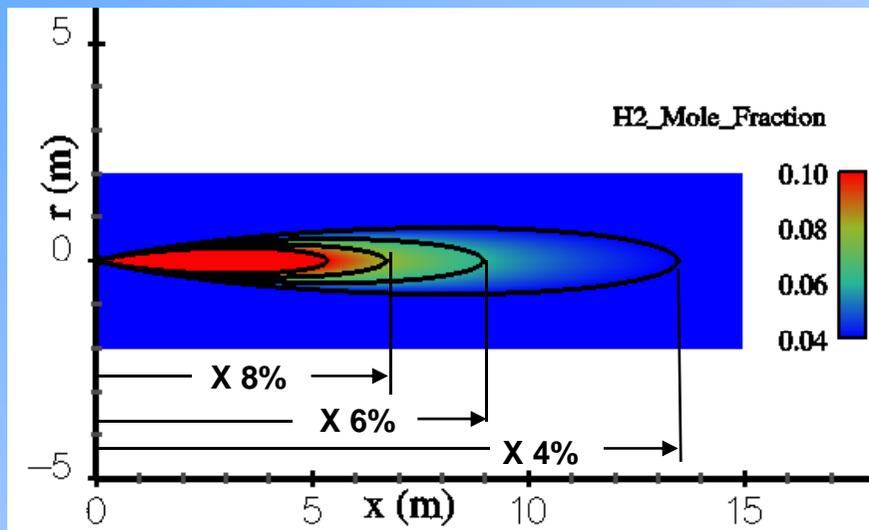
- Model based on experimental data for entrainment and mixing in high momentum turbulent jets
 - Verified against natural gas and ethylene jets data of Birch et al., 1984
 - Model adapted to H₂ properties
 - Verified against H₂ Navier-Stokes calculations

Comparison of Predicted Jet Centerline Concentration Fall-Off with Natural Gas Data



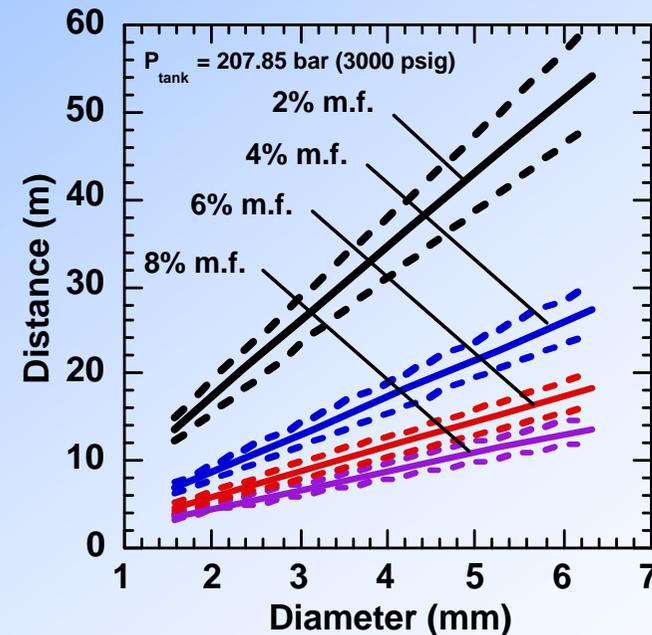
We have computed unignited H₂ jet concentration decay distances over the range of diameters and pressures.

Simulation of H₂ Concentration in a High Momentum Jet Exiting into Air
207.8 bar (3000 psig), Dia. = 3.175 mm (1/8 inch)



- Lower Flammability Limits for H₂*
 - Upward-propogating flame - 4% m.f.
 - Horizontal-propogating flame - 7.2% m.f.
 - Downward-propogating flame - 9.5% m.f.

Pressure = 207.8 bar (3000 psig)

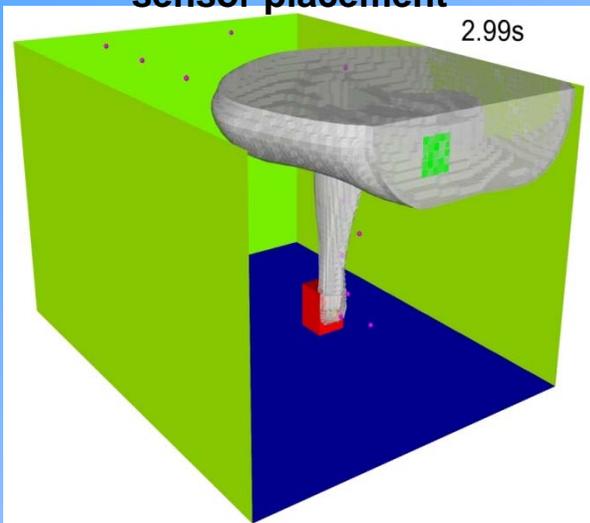


- 10-20% uncertainty in hazard length scales

*(Coward and Jones, 1952)
(Zebetakis, 1965)

Experimental scenario analysis and CFD modeling were used to evaluate indoor refueling hazards.

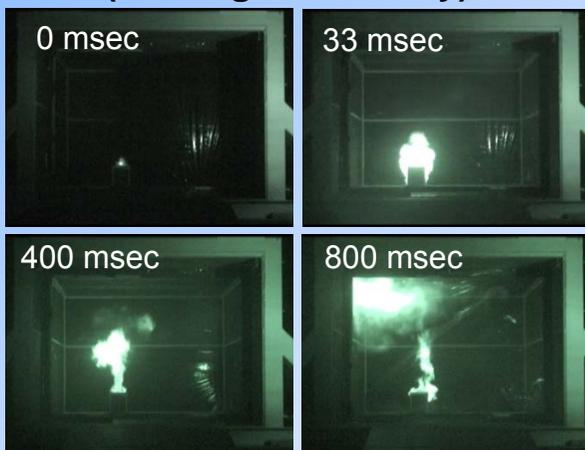
CFD used to evaluate optimal sensor placement



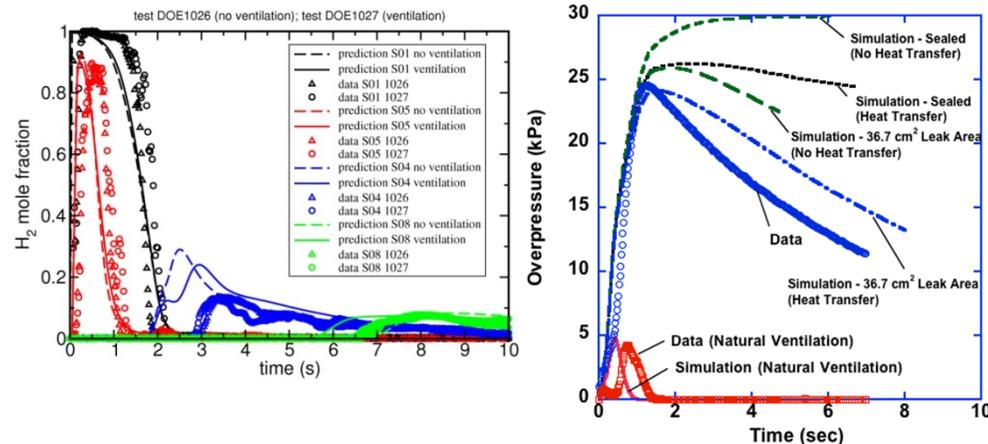
Large-scale experiments conducted in blast-hardened Sub-Scale Warehouse at SRI Test Site



Flame front propagation imaged (3 sec ignition delay)



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

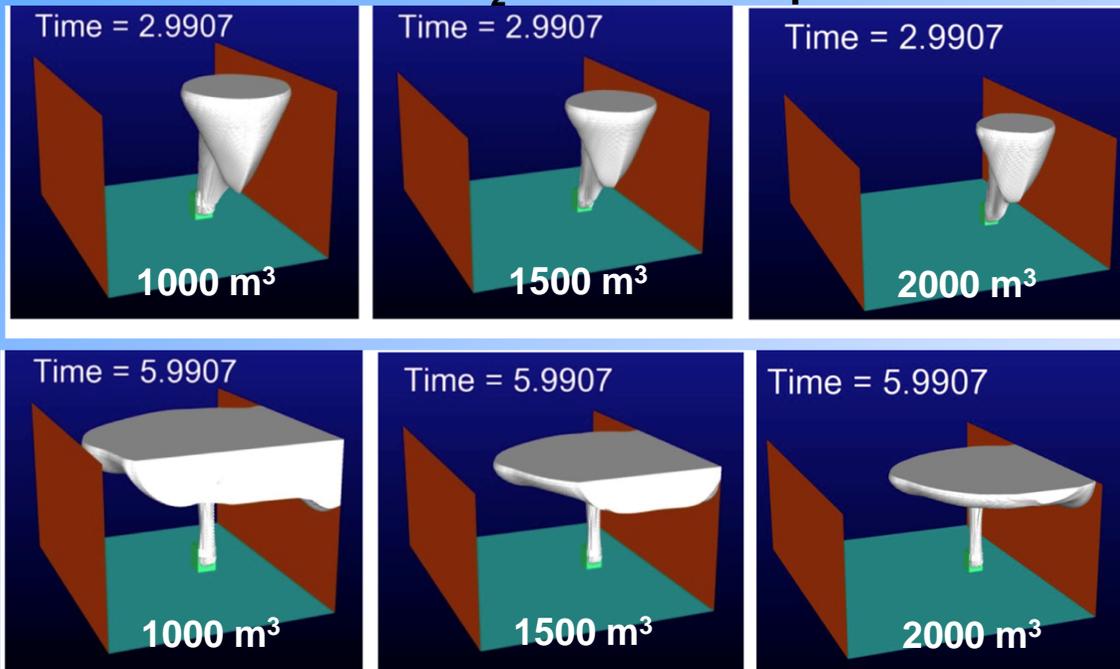


CFD matched the data if wall heat transfer and warehouse leak area corrections were applied.

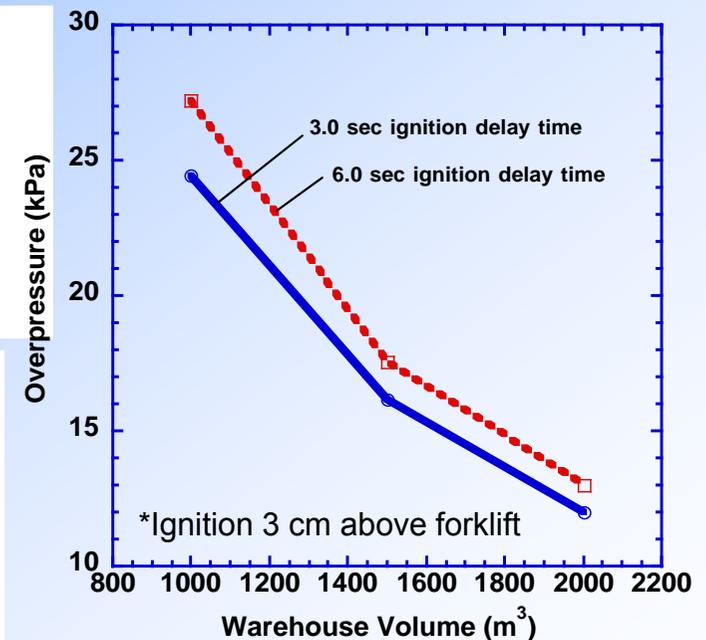
Validated CFD approach used to evaluate full-scale scenarios and inform indoor refueling requirements.

- **Forklift tank and release parameters:**
35 MPa storage pressure, 0.8 kg H₂, 6.35 mm orifice dia.
- **Warehouse:**
7.62 m ceiling, 3 room volumes

Flammable H₂ Cloud Development



Overpressure vs. Warehouse Volume



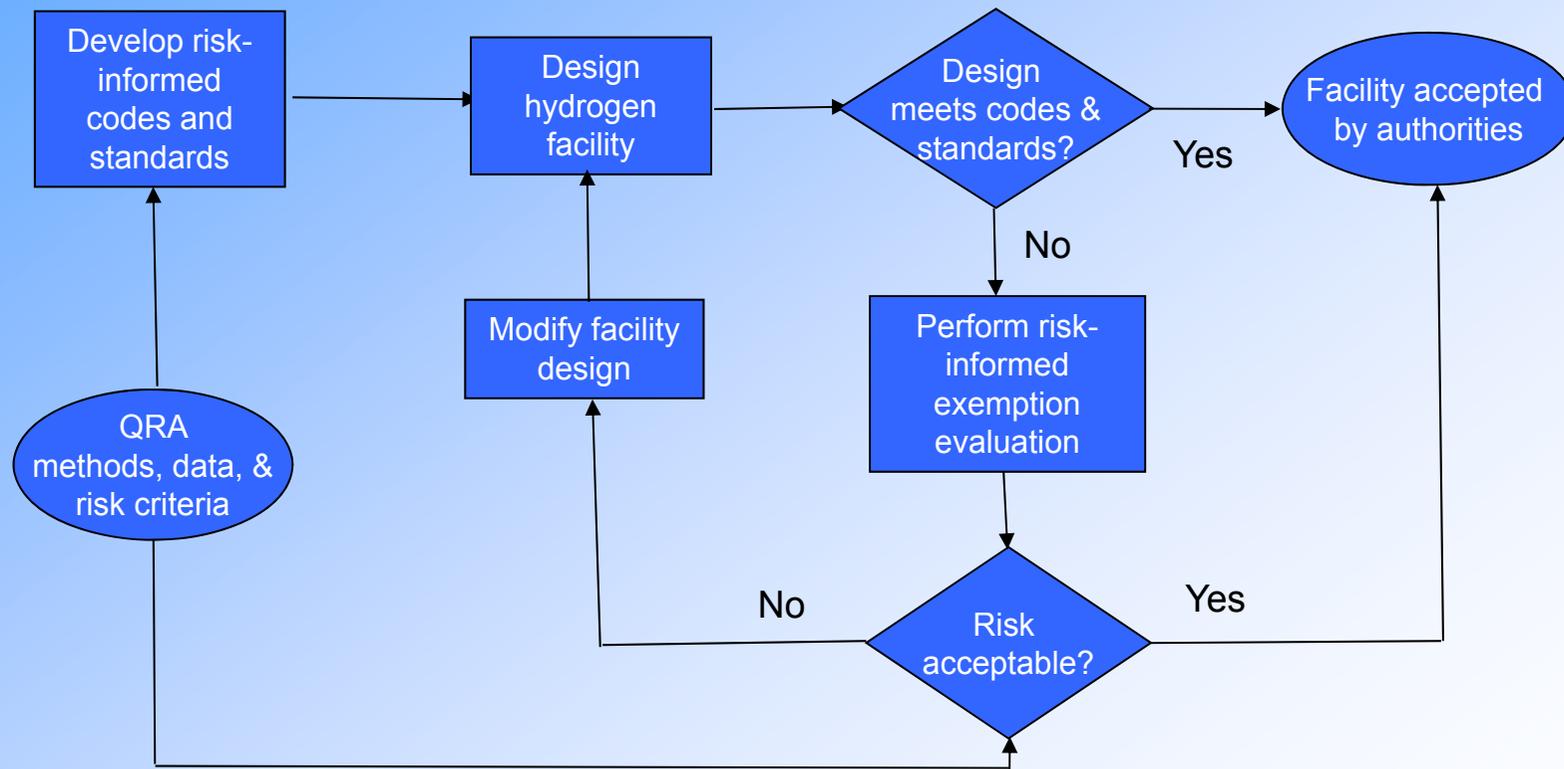
Can dispersion be predicted from integral plume & ceiling layer models?
Do obstacles induce turbulent enhancement of the deflagration wave?
Are reduced order overpressure models using flammable volumes viable?



Risk-Informed Approach for Permitting Hydrogen Facilities

- Challenge is to have a permitting process that is relatively simple and cost-effective but ensures a safe design
 - Deterministic approach can introduce unnecessary conservatism
 - Higher cost and restrictive siting
- A risk-informed process combines risk information, deterministic analyses, and other considerations to make decisions
 - Can include defense-in-depth and safety margins in design to address uncertainties

Risk-Informed Framework for Permitting Hydrogen Facilities





Peer Review

- Peer review of facility QRA adds credence to QRA quality
- Review can be done to confirm conformance with QRA standard and use of acceptable methods
- Reviewers should have knowledge of QRA elements
- Reviewers should be independent to avoid conflict of interest



Tools for Supporting the Permitting Process

- Several groups have developed or are developing tool kits to facilitate the permitting of hydrogen fueling stations:
 - KIT
 - U.S. Department of Energy
 - Canadian Hydrogen Safety Program – (includes QRA tool)
 - HySafe initiatives including HyQRA



Uncertainty Assessment

Uncertainty arises from many sources

- Inability to specify initial and boundary conditions precisely
 - Cannot specify result with deterministic model
 - Instead, use probabilistic models (e.g., tossing a coin)
- Sparse data on initiating events, component failures, and human errors
- Lack of understanding of phenomena (e.g., auto-ignition conditions)
- Modeling assumptions (e.g., leak size)
- Modeling limitations (e.g., inability to model human errors of commission)
- Incompleteness (e.g., failure to identify system failure mode)



Addressing Epistemic Uncertainties

- Parameter uncertainty addressed by Monte Carlo simulation
- Modeling uncertainty usually addressed through sensitivity studies
 - Research ongoing to examine more formal approaches
- Completeness addressed through comparison with other studies and peer review
 - Some issues (e.g., design errors) are simply acknowledged as limitations
 - Defense-in-depth in facility design can be used to address unknowns