Project ID # SCS011

R&D for Safety Codes and Standards: Risk Assessments

Sandia National Laboratories

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Overview

Timeline

- Project start date: Oct. 2003
- Project end date: Sept. 2015
- Percent complete: *80%*

Barriers (2012 MYRD&D)

- A. Safety Data and Information: Limited Access and Availability
- G. Insufficient technical data to revise standards
- L. Usage and Access Restrictions – parking structures, tunnels and other usage areas

Budget

- Total project funding
  - DOE share: $0.7M
- Funding received in FY11 : $0.2M
- Planned Funding in FY12: $0.5 M

Partners

Industry: HIPOC, FCHEA, Air Products, Nuvera

Govt: NREL, PNNL

SDO/CDO: NFPA, ICC, ISO

International: IEA, IPHE

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Coordinate critical stakeholders and research to remove technology deployment barriers

Partnerships with industry, labs, academia

Identify R&D needs → *Perform High-Priority R&D* → *Impact Codes and Standards*

Harmonize Internationally

Regulations, Codes and Standards (SAE, NFPA, ICC)
International Standards (ISO, GTR)
International Agreements (IEA, IPHE)

- Metrics for Success
  - Number of codes, standards, regulations impacted
  - Degree of harmonization
  - Number of systems qualified based on developed standards

Program Structured to address critical R&D to impact RCS

SNL R&D for H_2 Safety, Codes & Standards

Develop Science Basis for H_2 SCS

- Quantify H_2 relevant failure modes & scenario variables
- Hydrogen effects in structural materials
- Experiments & modeling to describe release/ignition behavior
- Validated simulations & engineering for consequence modeling

Impact & Harmonize H_2 SCS Development

- Consequence & Risk
- International Harmonization

Standards advocacy ensures transfer of science-based H_2 SCS knowledge to code development committees.

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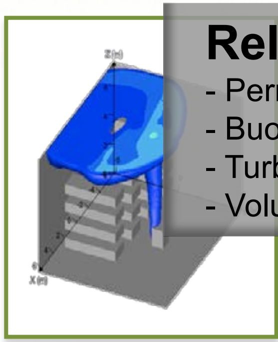
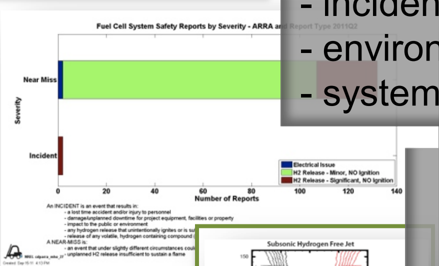
Risk-Informed Approach

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



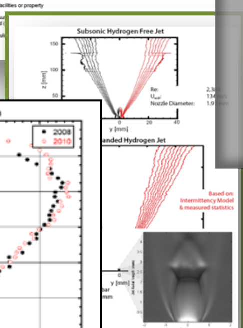
Release Probability
- Permeation
- Buoyant creeping flow
- Turbulent jet
- Volumetric rupture

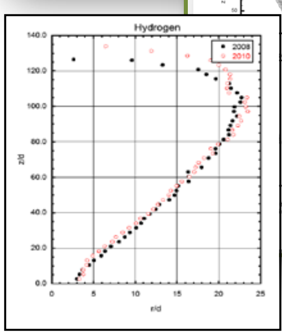
Informed Input
Code development groups, industry, regulators and code enforcers



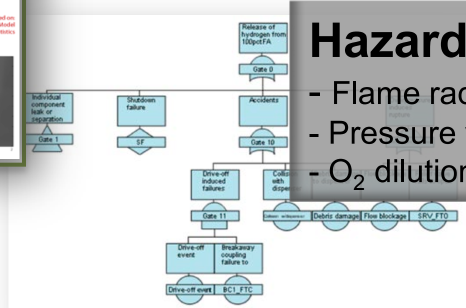
Field Data Input
- incident data,
- environmental/human factors,
- system design/mitigation

QRA





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



Hazard Probability
- Flame radiation
- Pressure wave (deflagration/detonation)
- O_2 dilution/depletion

Harm Probability
- Burns
- Lung damage
- Shrapnel wounds
- Building collapse

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FY12 Objectives

Target RCS: Building codes (NFPA 2, ISO)

- Understand confined releases of hydrogen through experimentally validated simulations
- Update risk model based on consequences of confined spaces
- Inform NFPA 2 Code Development Committee
  - Identify discrepancies and editorial changes
  - Identify, perform and report on consequence modeling efforts
  - Solicit committee input for risk tolerance of target applications
  - Perform and report results of Quantitative Risk Assessment based on risk tolerance input*
- Harmonize other codes and standards
  - NFPA 2/502 – Tunnels
  - ISO, CSA, UL, ICC, etc.

*Not all committee concerns require QRA to inform committee actions (e.g., minimum room volume for indoor fueling changes proposed after discrepancy identified during consequence modeling)

Accomplishments: Overpressure Consequences from Indoor Leaks

- **Results:**
  - The assumed leak diameter heavily influences consequence
  - Min leak diameter required for any consequence regardless of frequency (assuming code compliant ceiling height; 7.62m)

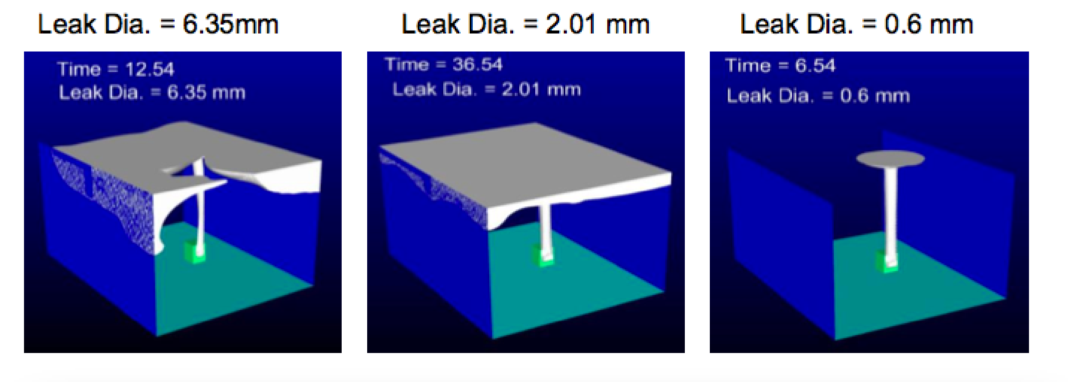
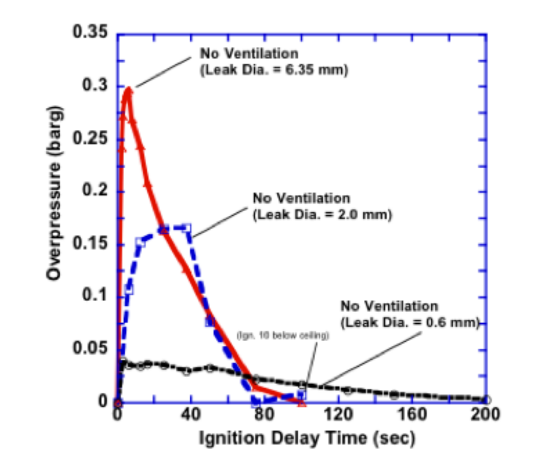


Figure 1. Simulations showing maximum flammable hydrogen cloud (4%–75% mole fraction) volume for different diameter leaks (6.35 mm, 2.01 mm, 0.6 mm) for the 0.8 kg forklift release for full-scale warehouses with a 7.62-m high ceiling and volume of 1000 m^3 (without ventilation). Initial tank pressure was 35 MPa and the elapsed time is shown in seconds.



- **Code development committee actions:**
  - Confirmed ceiling height requirement
  - Begin investigation of leak frequencies by size to re-evaluate input to risk model
  - Begin investigation of ignition probabilities based on impact of delayed ignition

Figure 2. Simulations showing peak ignition overpressure in a well-sealed (100%) full-scale warehouse for a 0.8-kg forklift release where ignition occurs 3 cm above the top of the forklift and the ceiling height is 7.62 m. Results are shown for leak diameters of 6.35 mm, 2.01 mm, and 0.06 mm. Initial tank pressure was 35 MPa.

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Accomplishments:

Evaluate Effect of Obstacles
(Indoor Releases)

➢ Results:

- Evaluated influence of obstacles (e.g., shelving in warehouses) on flammable cloud
- Result – for conditions considered, obstacles do not significantly impact release or overpressure characteristics

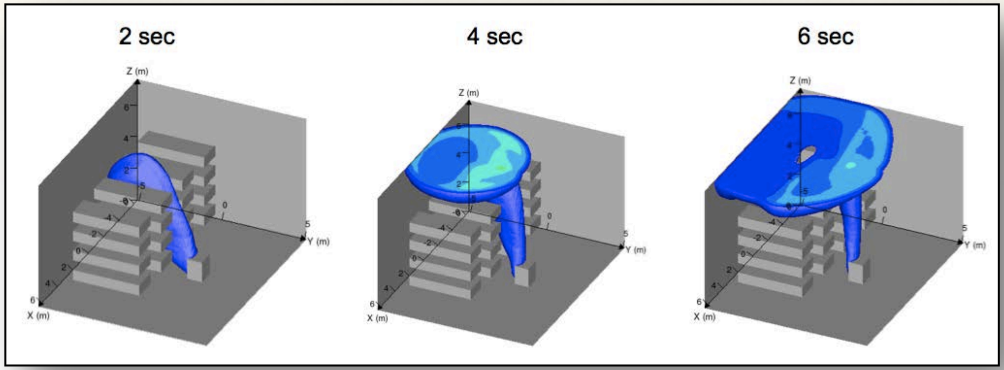

Fig. 1 Flammable volume as a function of time for 6.35mm leak

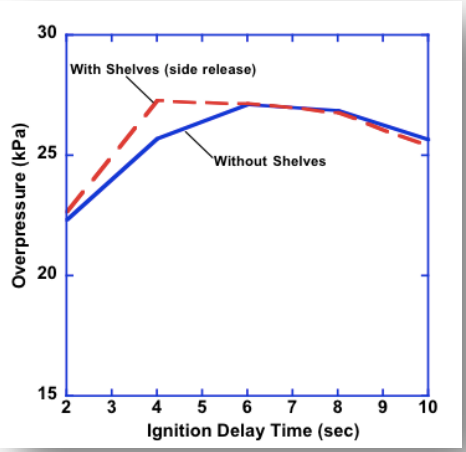

Fig 2. Overpressure with and w/o obstacles

➢ Code development committee actions:

- Confirmed influence of obstacles or other room contents on the release characteristics and overpressures.
  - Need to increase minimum room volume requirement
  - Room contents ‘factor’ not required.
- Future Work – Committee requested consequence simulation based on room size – given the ceiling height requirement

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Quantitative Risk Assessment

1. Assume that hydrogen release is the only change in hazard vs. current use scenario (e.g., forklift operation, automotive refueling, etc.)
2. Describe scenarios that occur after an H2 release (Event Sequence Diagram)
   - Use events records (from H2, CNG, and gasoline fueling) to build an Event Sequence Diagram to describe the scenarios that can occur after an H2 release
3. Describe the events that can lead to H2 releases (Fault Tree)
   - Use accident records from H2, CNG, and gasoline fueling. Also use component failure mechanisms.
4. Use frequency data to quantify the Fault Tree
   - H2 component leakage rates from LaChance work (presented at 2011 AMR)
   - Component failure rates from offshore oil and nuclear industry
5. Use existing probability models to quantify the probability of ignition, given a leak
6. Use best estimate to determine the consequences (number of fatalities) from each accident scenario (release behavior models, ignition probability, etc.)
7. Calculate predicted Fatal Accident Rate (FAR). Compare fatality rates with other industries
8. Communicate results - Participate in code development committee interpretation of QRA results

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Accomplishments: Expanded Fault Tree

<u>Additional Fault -Tree Elements:</u>

Shutdown failure:

Unit fails to shutdown upon demand (e.g. e-stop)

Accidents:

Human factor influenced failures such as:

- Drive Off (fuel hose breakaway)
- Collision with Dispenser

Evaluation of individual contributions from each initiating event allow for elimination of events which do not significantly contribute.

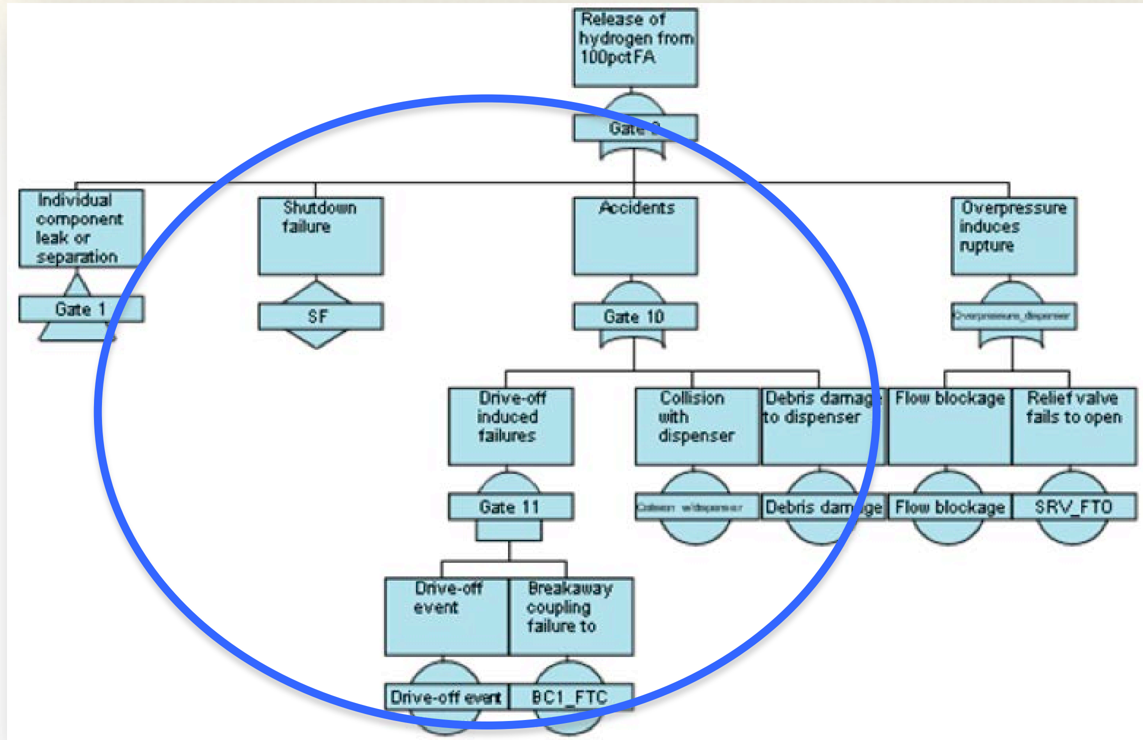


Fig 1. Fault Tree for hydrogen release in which the equivalent flow orifice is the same size as the flow area. This the assumed worst case consequence with the largest flammable cloud.

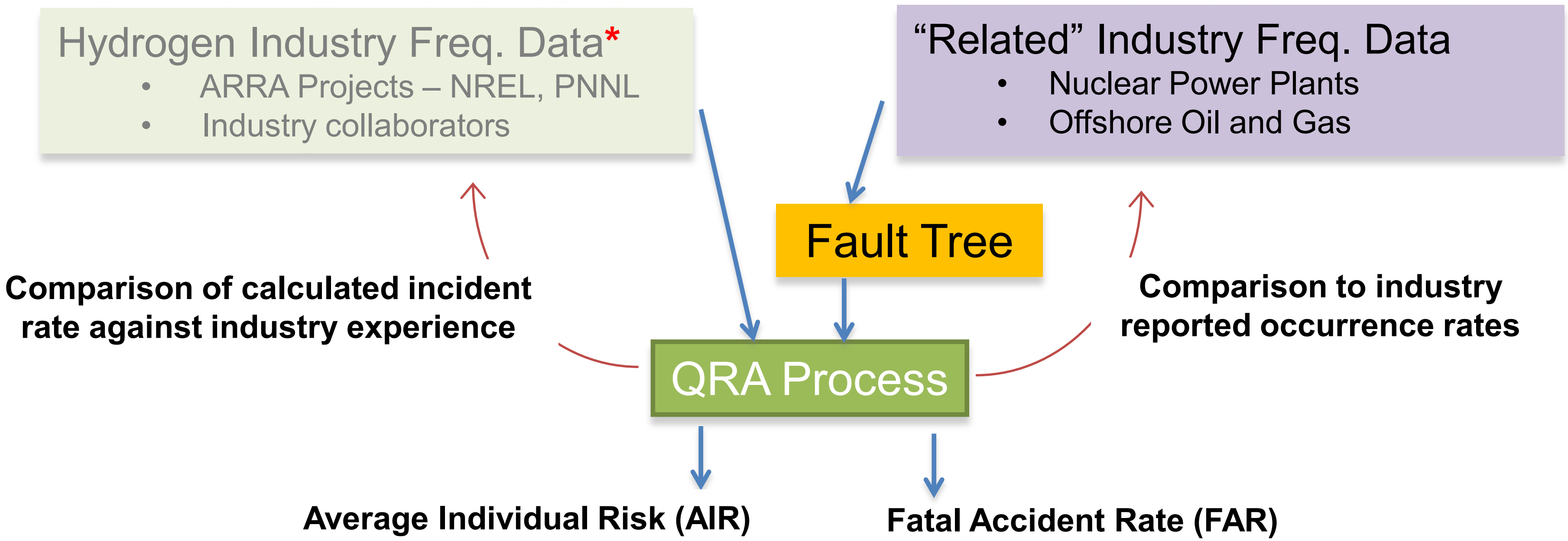
Lack of hydrogen industry frequency data, particularly denominator values: (number of demands or annual exposure time) forced extensive reference review.

Accomplishments:

Established Process for Input Data

The Fault Tree relies on frequency and probability data to establish frequency of hydrogen releases

Frequency data from “related” industries requires significant effort to correctly correlate to commercial hydrogen.



<u>Initial Results:</u> Using only “related” industry data the average individual risk (AIR) is similar to accepted levels in raw material extraction industries. Significant ichanges in AIR expected using hydrogen specific data.

*Hydrogen industry frequency data from “spearhead” markets (forklifts and cell towers) and demonstrations could be very beneficial. **Access to data is a barrier to accurate QRA.**

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Accomplishments:

Influence on Fire Code Updates

QRA Process provides more than QRA analytical results

Influences on NFPA 2 from current QRA process

Review code requirements

- Developed generic indoor fueling system model which:
  - Identified vague requirements in NFPA 2-2010 ch. 10
  - Identified mis-match in previous consequence modeling (e.g. room size)
  - Promoted discussion regarding several system design requirements (e.g. venting indoors vs. outdoors, passive flow restriction, etc.)

Develop release and consequence modeling for specific scenarios

- Iterate modeling with committee input to ensure accuracy
- Evaluate nuances to indoor fueling vs. previous consequence models
- Promoted discussion regarding building code requirements (fueling areas vs. fueling rooms)
- Future work – update QRA model with consequence results

Update event sequence and fault tree models

- Work with industry partners to develop and quantify event sequence models
- Work with industry and research partners to quantify frequencies

Future Work – Provide QRA results to inform committee proposals (proposal deadline Jan 2013)

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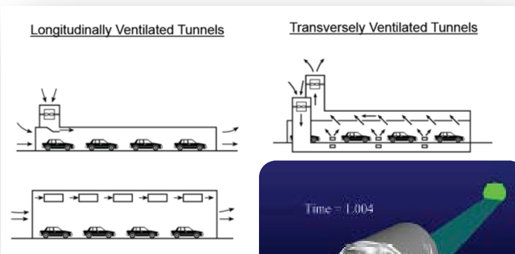
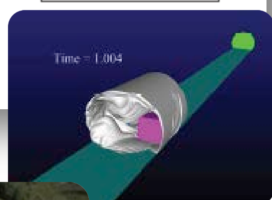
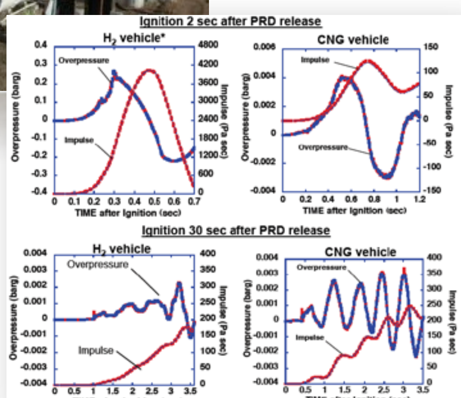
Harmonization of NFPA 2 (Hydrogen) and NFPA 502 (Tunnels)

Accomplishment:

Previous accomplishment:
Determined no increase to public risk of hydrogen vehicles in tunnels based on experimentally validated consequence simulation.







Current Accomplishment:
Presented consequence modeling results and analysis to NFPA 502 committee (at request of NFPA 2 tunnels task group)

Discussion result:

- Committees accept risk analysis results
- Acknowledged confidence in results based on thorough scientific approach
- Confirmed audience for hydrogen safety, code and standards activity is larger than hydrogen community

Future Work

FY12

- Develop consequence simulations validated by previous work for indoor scenarios
- Produce QRA results for indoor fueling with the addition of frequency data provided by industry partners
- Continue efforts to link safety data reporting efforts at partner research institutions
- Address inefficient QRA software tools, development or process improvement
- Compare QRA results with reported risks for industrial truck operation
- Engage with researchers not yet collaborating with IEA (China)

FY13

- Develop ignition probability models based on current behavior research
- Facilitate hydrogen industry adoption of QRA; database, first order tools and published methods
- Produce comprehensive reference for hydrogen system QRA

Collaborations:

Industry and Research Partners

- **Leadership in NFPA 2 Refueling Task Group**
  - Task group members in active collaboration:
    - Air Products and Chemicals
    - Nuvera Fuel Cells
    - NREL
    - University of Quebec TR
- **Leadership roll in IEA Task 31 (previously 19) on Hydrogen Safety**
  - Hydrogen behavior and risk assessment research
- Participant role in various codes and standards efforts
  - SAE Interface and Safety Working Groups
  - NFPA 2 Tunnels, Generation, Separation Distances and Refueling working groups
  - CSA standards – HGV 4.3, HPIT2
  - HIPOC
  - FCHEA Transportation and Generation Working Groups
  - ISO TC 197 and IEC TC 105

H2CAN/Sandia collaboration on Hydrogen Safety

- Sandia hosted hydrogen safety workshop - April 11-12
- Workshop Goal: Coordinate hydrogen safety efforts between H2 CAN and US Programs

- Strong alignment of efforts identified at ICHS hosted by Sandia in Sept 2011
- Further reinforced by IEA Task 31 meeting in Jan 2012
- Identified several near-term risk and behavior collaborative topics
- Research roadmap presented during IEA Task 31 meeting – April 2012

Milestones

Deadline	Description
6/ 12	1) Perform and document required risk assessment (with input from NFPA 2 and others) for developing science-based risk-informed codes and standards for indoor refueling of hydrogen lift trucks or other vehicles
Progress Update	Model complete, reported results dependent upon availability of industry specific data. Model revisions underway based on input form NFPA 2 and others.
9/12	2) Perform scoping risk assessment for accident mitigation features for refueling stations and indoor refueling applications including development of any required data and new methodologies.
Progress Update	Partially based on results of milestone 1. Participant in NFPA 2 mitigation working group discussions.

Summary

- Sandia risk assessment methods enables deployment of hydrogen systems and infrastructure
- We have updated previous risk assessments
- We have compared risk assessment results to similar industry risk performance
- We have influenced code development beyond NFPA 2
- We have partnered with industry and other research institutions to ensure our results are based on relevant data and provide helpful insight

For more information see:

- ***R&D for Safety Codes and Standards: Hydrogen Behavior (SCS010)***
- ***R&D for Safety Codes and Standards: Materials and Components Compatibility (SCS005)***

Technical Back-Up Slides

Materials Testing Influenced Risk Modeling

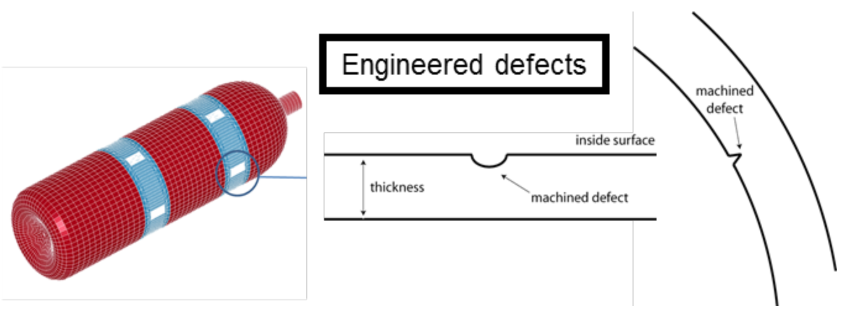
Failure Modes from Tank Testing:

- O-ring extrusion
- Leak before burst *(through-wall cracks in type 1 vessels)*

→ Pressure Data used to calculate Equivalent Leak Diameters

O-ring extrusion between fitting and tank

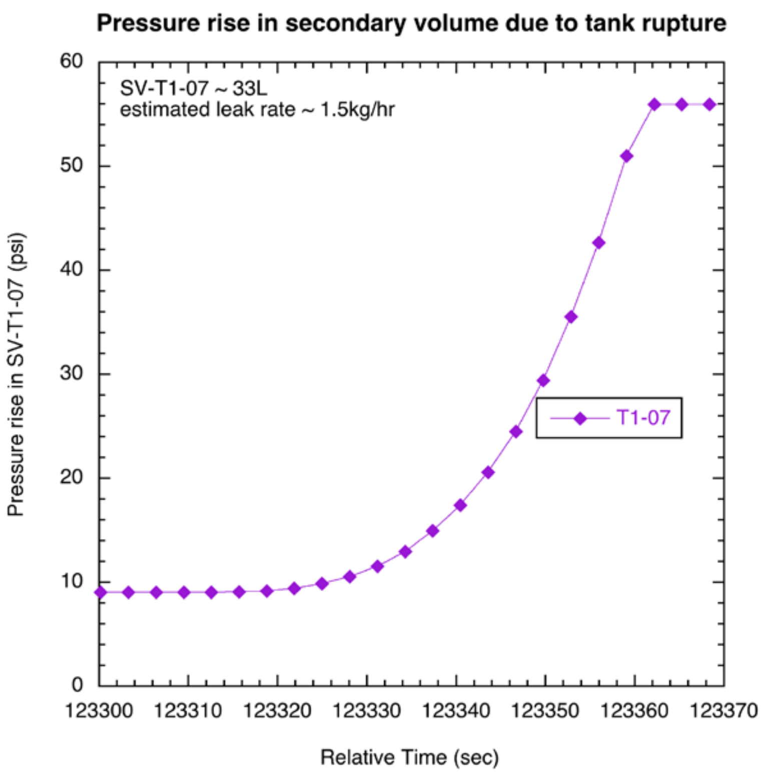
→ Leak rate: 0.01 kg/hr → Equivalent Leak Diameter @ 35Mpa: 0.015mm

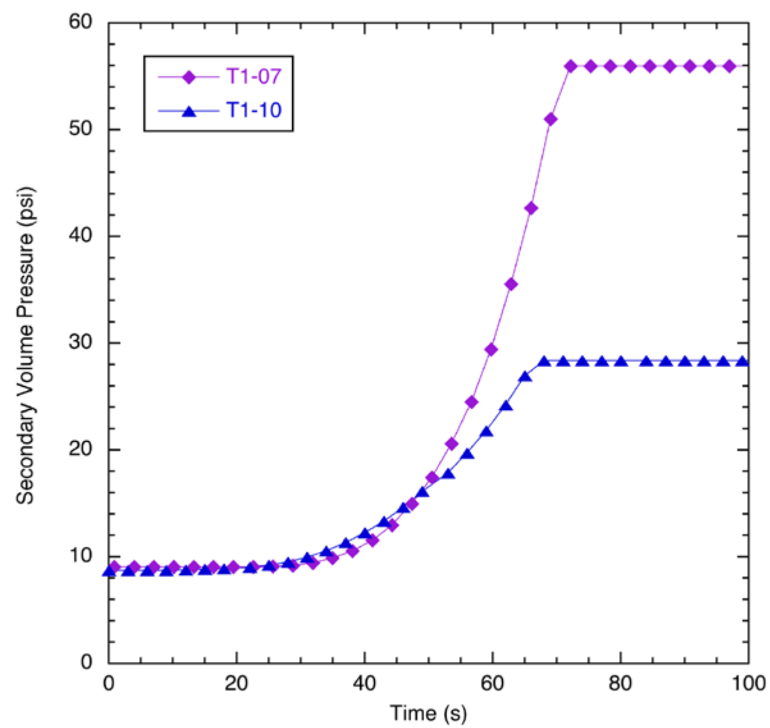


→ Leak rate: 1.3 kg/hr → Equivalent Leak Diameter @ 35Mpa: 4.36mm

Estimation of hydrogen flow through leaking crack

- Penetration of crack through-wall produces pressure rise in secondary containment that is measurable
- Since volume in secondary containment is known (temperature assumed to be constant), the mass flow rate of hydrogen into secondary containment can be estimated as ~1.5 kg/hr



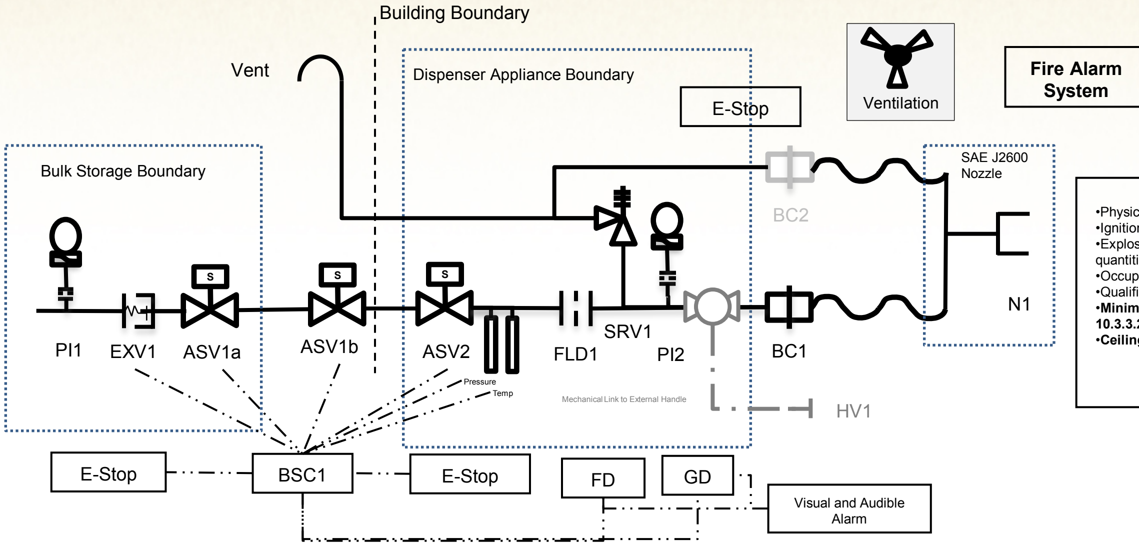


Example of 'generic' Indoor Refueling System P&ID based on Code requirements

Indoor
Non- Public
Fast Fill*
Dispenser P&ID

Code Compliant

*Note – Fast Fill Doesn't exist in IFC; limits H2 flow to 12 SCFM (0.027kg/min) IFC 2309.3.1.2 (3)



Other Safety Requirements

- 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)**

P&ID Tag	Description	Code/Standard Reference	P&ID Tag	Description	Code/Standard Reference
ASV1a	Auto shutoff (solenoid) valve (Source Valve)	6.20 - Source Valve 7.1.21 - Accessible manual or automatic emergency shutoff valve (HGV 4.4/HGV 4.6 Component Standards)	PI1/PI2	Dispense delivery pressure indicator (6" circular mechanical gauge; 0-10000psig)	10.3.1.5.3 – indication of storage, dispenser discharge pressure 10.3.1.5.2 - 0.055in opening at inlet connection NOTE – a third pressure gauge at compressor discharge is also required (10.3.1.5.3)
ASV1b	Auto shutoff (solenoid) valve (building isolation)	7.1.21.2 …at the point where the system piping enters the building 10.3.1.18.4 – building isolation valve required	SRV1	Safety (Overpressure) relief valve (6000psig)	10.3.1.4.2.3 – overpressure device shall be installed; 10.3.1.4.2.4 – setting shall not exceed 140% of service pressure 10.3.1.10.5 – inspected every 3 years
ASV2	Auto shutoff (solenoid) valve	7.1.21.2 …at the point of use 10.3.3.2.2.7 (A) – Automatic shutoff valve	N1	Nozzle	10.3.1.14.7 – transfer system capable of depressurization to facilitate disconnection 10.3.1.15.1 – SAE J2600 nozzle required
EXV1	Excess Flow Device	7.1.22 Excess flow control – leak detection and emergency shutoff or excess flow control (Component Standard?) 10.3.1.18.3 - excess flow valve requirements	Vent	Vent Pipe and Vent Pipe Termination	6.16 - CGA 5.5, 7.1.17,
FD1	Flame detector	10.3.1.19.1 – gas, flame detected at any point on the equipment 10.3.3.2.2.4 – Fire detection system tied to local visual and audible alarm	Ventilation	Required ventilation for indoor fueling	**10.3.3.2.2.2 – in accordance with 10.3.2.2.1.6** 10.3.2.2.1.6 - required by clause (A) 10.3.2.2.1.6 (D) (1) continuous or activated by h2 detector
GD1	Gas detector	10.3.1.19.1 – gas, flame detected at any point on the equipment **10.3.3.2.2.7 (E) – similar to 10.3.1.19.1 with additional requirements: activation shuts down dispenser, visual/audible alarm and functions during maintenance**	**Estop x 3**	Manual Emergency Stops	10.3.1.18.5 – local and remote located manual shutdown **10.3.3.2.2.6 – Emergency shutdown device similar to 10.3.1.18.5 with more specific location requirements** 10.3.3.2.2.6 (A) – 3rd manual shutdown device on the dispensers
BC1	Breakaway coupling (dispensing hose)	10.3.1.18.6 – breakaway coupling required – NGV 4.4 compliant, breaking force	H1	Flexible dispensing /vent hose	10.3.1.1 – listed or approved 10.3.1.8 – Hose connections (note – no reference to HGV 4.4 10.3.1.11.2 – Hose assemblies 10.3.3.2.2.2 (H) – limited to 25ft. Protected from abrasion or driven over by vehicle
FLD1	**Flow limiting device**	**10.3.3.2.2.2 (F) max fueling rate 2kg/min**	BC2	Breakaway coupling (vent hose)	Not required
Fire Alarm	**Fire Alarm System**	**10.3.3.2.2.5 – dispensing area local fire alarm system, pull box between 20 and 100 ft of dispenser, at nearest exit from area, pull boxes shutdown dispenser**	**HV1**	**Hand Valve – "quarter turn" manual shutoff**	**10.3.3.2.2.7 (B) - not required when ASV 2 is located immediately upstream and a control arm or ESD closes the valve**
BSC1	Building Safety Circuit (Logic Controller)	10.3.1.11.6 – controller performs 5 sec pressure test prior to fueling 10.3.1.11.7 – repeat integrity check at 3000 psi 10.3.1.18.7 – control circuit requirement for manual reset after emergency stop activation 10.3.3.2.1.9 – manual restart after emergency activation 10.3.3.2.2.2 (C) automatic shutoff control when max fuel quantity per event or vehicle fueled to capacity 10.3.3.2.2.2 (G) – references 10.3.1.11.6 and 10.3.1.11.7 10.3.3.2.2.7 (G) – overpressure and over temperature sensing capabilities (assume that this could be communication with vehicle)			

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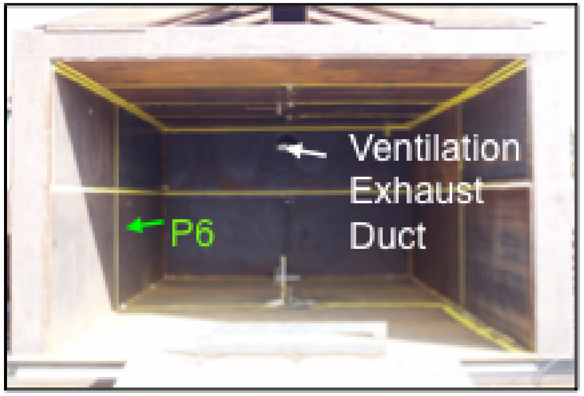
Technical Development of FAR and AIR

- Potential Loss of Life (PLL) is expressed as follows:
- $PLL = \sum_n \sum_j (f_{nj} \cdot\ c_{nj})$
  - Where f_nj is the frequency of an accident scenario n with (personnel) consequence j
  - And c_nj is the expected number of fatalities for accident scenario n with (personnel) consequence j. n is the total number of accident scenarios in all ESDs. J is the total of personnel consequence types.

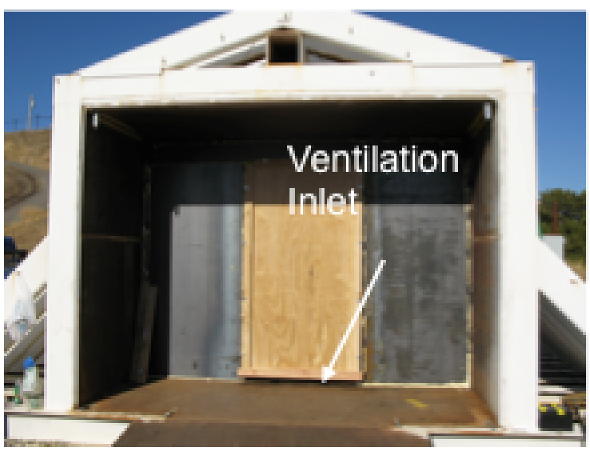
- $FAR = \frac{PLL \cdot 10^8}{Exposed\ hours} = \frac{PLL \cdot 10^8}{N_{staff} \cdot 8760}$
- $AIR = H \cdot FAR \cdot 10^{-8}$ \label{eq:AIR}
  - Where N_staff is the average number of personnel in the facility and H is the number of hours spent in the facility, per individual.

Ventilation has marginal impact on pressure for these conditions

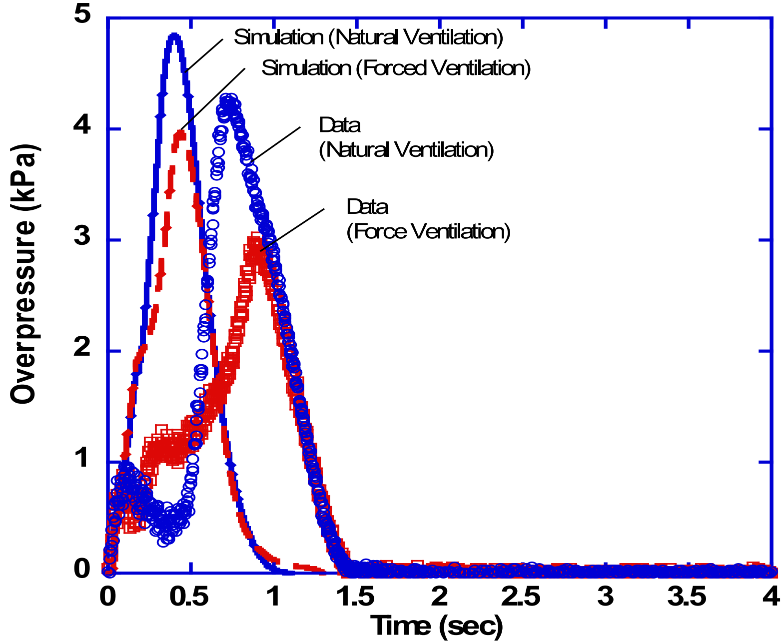
Interior of Sub-Scale Warehouse Showing Vent in Backwall



Front of Sub-Scale Warehouse showing added vent at the bottom of plywood panel



Comparison of Simulations and Experiments for Deflagration Overpressure in Subscale Warehouse for Active (Forced) and Passive (Natural) Ventilation (3 sec ignition delay)



*Ignition above forklift with delay of 3 sec
P6 pressures shown

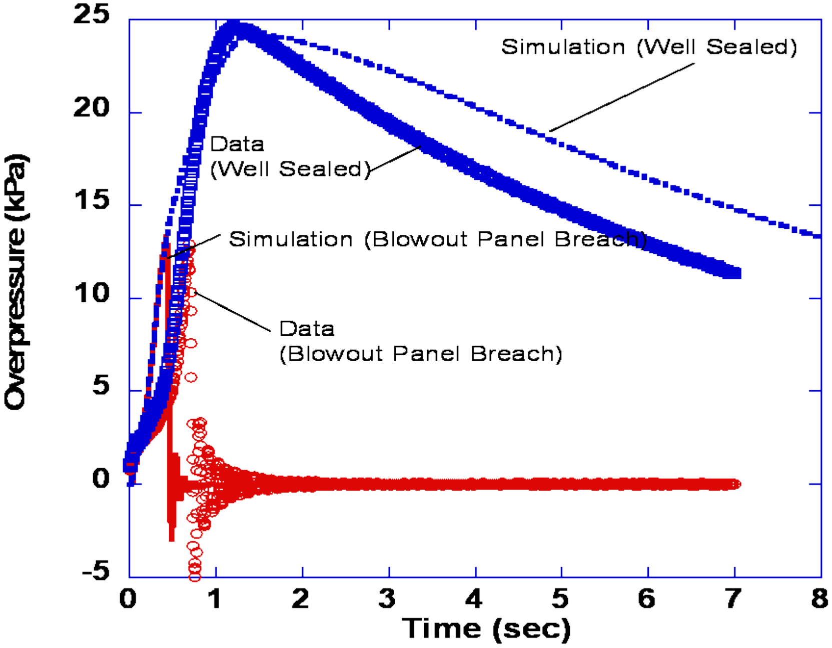
Pressure relief panels can be effective in reducing pressure

Sub-Scale Warehouse Showing Plywood Pressure Relief

Breach of Plywood Pressure Relief Panel

- Blowout panel provides overpressure relief
  - Plywood panel breaches at approximately 13 kPa

Comparison of Simulations with Experimental data for Deflagration Overpressure in Subscale Warehouse Well-Sealed and Blowout Panel Conditions (3 sec ignition delay)



*Ignition above forklift with delay of 3 sec
P6 pressures shown

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