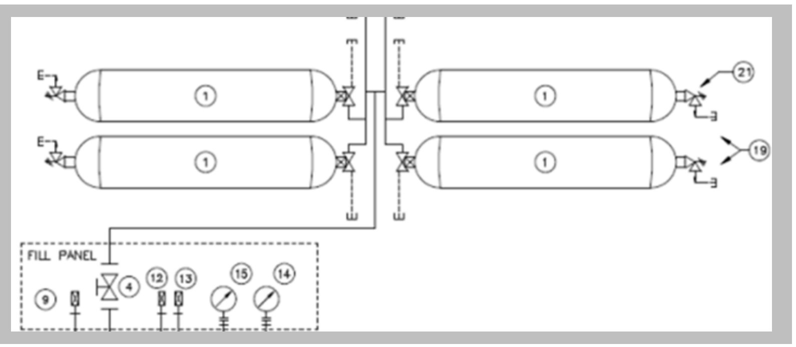
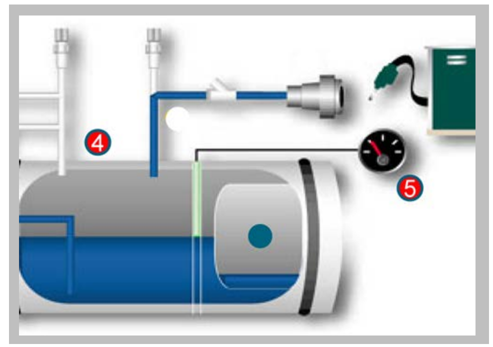
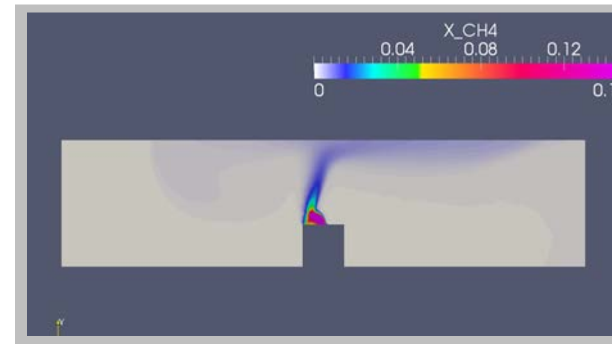
Exceptional service in the national interest







Risk-Informed LNG/CNG Maintenance Facility Codes and Standards

Project sponsored by the Clean Vehicle Education Foundation

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Sandia National Laboratories

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Project Motivation

- Improve codes and standards for gaseous fuel vehicle maintenance facility design and operation to reflect technology advancements
- Develop Risk-Informed guidelines for modification and construction of maintenance facilities using Quantitative Risk Assessment

Project Scope

Phase I

- Detailed survey of existing codes*
- Hazard identification and quantification
  - Conduct HAZOP study to provide a comprehensive list of credible hazard scenarios
  - Scenario modeling of four credible releases

Phase II

- Development of best practices to mitigate hazards
- Facility design guidance
- Proposed changes to existing fire protection codes

* note: published by CVEF

http://www.cleanvehicle.org/committee/technical/PDFs/GuidelinesDocumentFinal.pdf

Existing Code Issues

- Relevant Codes:
  - ICC includes IFC, IMC and IBC
  - NFPA 30A, 52, and 88A
- Code Concerns
  - Credible Release Amount - Existing CNG code (NFPA 30A) based on assumption that 150% of contents of largest cylinder would be released. Code requirements were not amended following PRD technology advancements.
  - Ignition Sources - Code guidance on location of ignition source restrictions needs to be updated based on credible leak scenarios and flammable concentration boundaries.
  - Ventilation Flow Rates - Discrepancies between applicable codes for ventilation rates and interlocks.

HAZOP Structure

- Failure Definition – Unexpected or uncontrolled release of natural gas (liquid or gaseous phase)

- Risk Class

	Consequence Class
2	Catastrophic release of natural gas (entire tank load)
1	Leak of natural gas (<entire tank)

Probability Class
High
Medium
Low

- HAZOP Spreadsheet

			Prevention Features			Mitigation Features				
Hazard Scenario	Causes	Consequences	Design	Administrative	Detection Method	Design	Administrative	Probability Class	Conse-quence Class	Risk Priority
Release of GNG through PRD	Failure of PRD to hold pressures below activation pressure (failure of o-ring etc.)	Total volume of system released potentially leading to fire, explosion, cryogenic burns or asphyxiation			Gas indicator alarm			Low	2	Low

Assumptions

- Activities

Service Maintenance and Repair Activities
Inspection of fuel storage and delivery piping, components (including PRD)
Inspection of fuel safety systems
Troubleshoot/ Testing
Exchange filters
Drain and replace fluids (non fuel system)
Replace non fuel system component (brakes, tires, transmission, etc.)
Repair leaking fuel system (repaired outdoors?)
Replace fuel system components (tank, PRD, valve, plug, pressure gauge, economizer, fuel gauge coaxial cable)
Leak Testing

Issues

Issues Impacting Failure Modes
Location of gas detectors (ceiling, exhaust ducts, pits)
Calibration of Gas Detectors in the Facility
Ventilation system - adequate flow (5 acph, always on, powered
Beam Pockets in Ceiling, dead air zones
Heaters, Lights, fan motors (ignition sources) > 750 to 800 ^{o}F
No odorant in LNG
Interlocks that activate on gas detection
Use of power tools, lights, radios, cutting & welding (ignition sources)

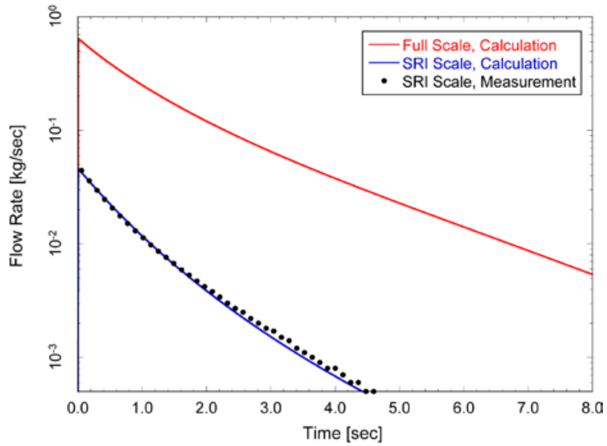
Operational States

			Operation State	Fuel System State
Outdoor	Preparation for Service	1	Defueling	Entire fuel system (FMM and tanks) being evacuated
		2	Cracking of fuel system (FMM only)	Tank valved off, FMM being evacuated
		3out	Dead vehicle storage	Fuel system charged but idle, key-off
Indoor		3in	Dead vehicle storage	Fuel system charged but idle, key-off
	Service	4	Engine operation/idling (during testing, fuel run down, inspection and troubleshooting activities)	Key-on operation
		5	Service on non-fuel systems	Tanks valved off, FMM evacuated (Run Down)
		6	Service on fuel system [Group 1]	Entire fuel system evacuated
		7	Service on fuel system [Group 2]	Tanks valved off, FMM Run Down then cracked
	Restart	8	System refilling OR valve opening followed by restart	Fuel system recharging

HAZOP Results

- Scenarios Selected for Modeling
    1. Fully-fueled LNG vehicle exceeds hold time in facility resulting in Pressure Relief Device (PRV) controlled release of gaseous NG
    2. Pressurized residual NG downstream of isolation valve and heat exchanger of LNG vehicle released when fuel system purged by technician.
    3. Pressurized residual NG downstream of isolation valve of CNG vehicle released when fuel system purged by technician. CNG fuel system quantity can be an order of magnitude greater than for LNG fuel systems due to larger volumes and pressures.
    4. Entire contents of CNG cylinder (700L, 250 bar) released due to mechanical failure of the PRD
- Remainder of credible scenarios form basis for follow-on QRA work for specific code requirements

Simulation Methodology

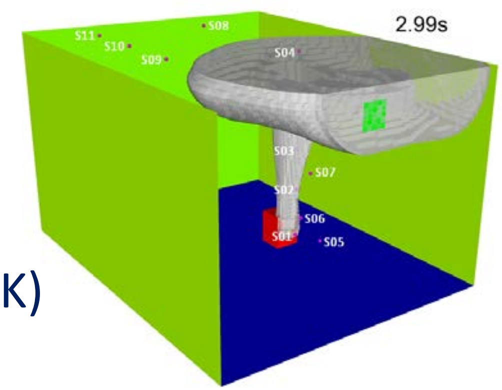


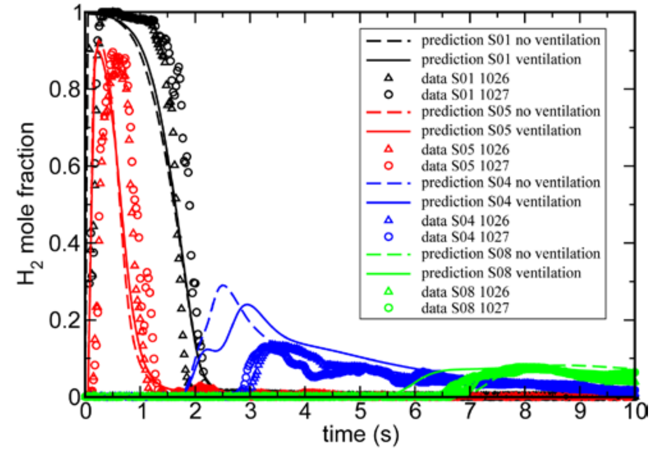
Blowdown release rates calculated via Sandia network flow solver (NETFLOW)

Winters, SAND Report 2009-6838.

Sandia FUEGO flow solver

- Finite volume
- Compressible Navier-Stokes
- k-ε turbulence model
- No slip isothermal walls (294 K)
- ~10 cm mesh spacing



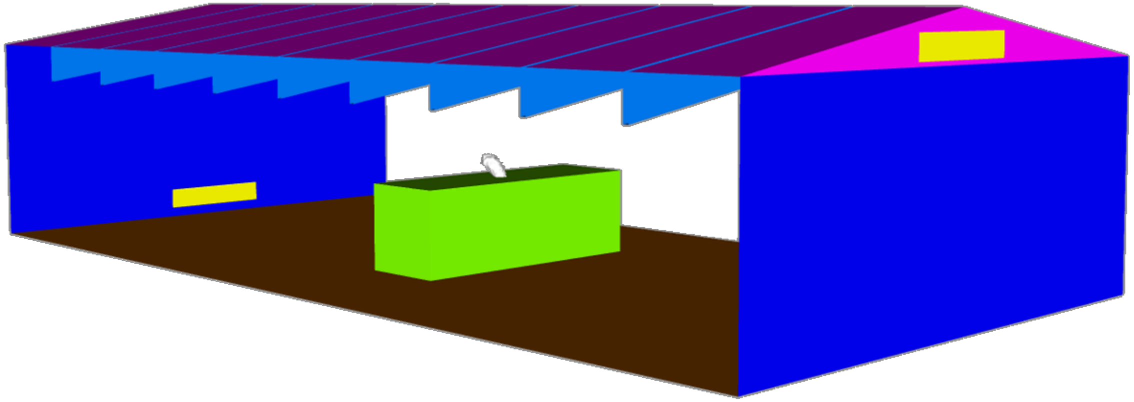


Houf et al., Int J H2Energy, 2013.

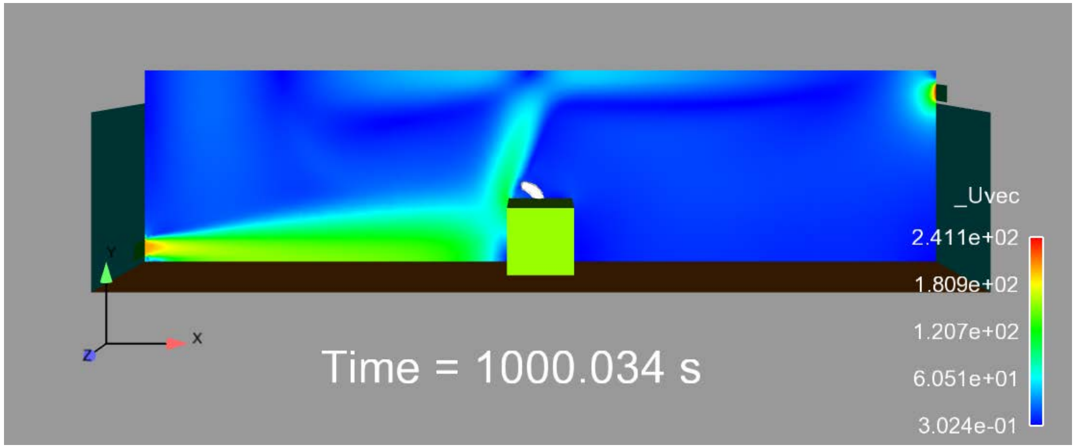
Methodology previously validated against large-scale hydrogen blowdown release experiments

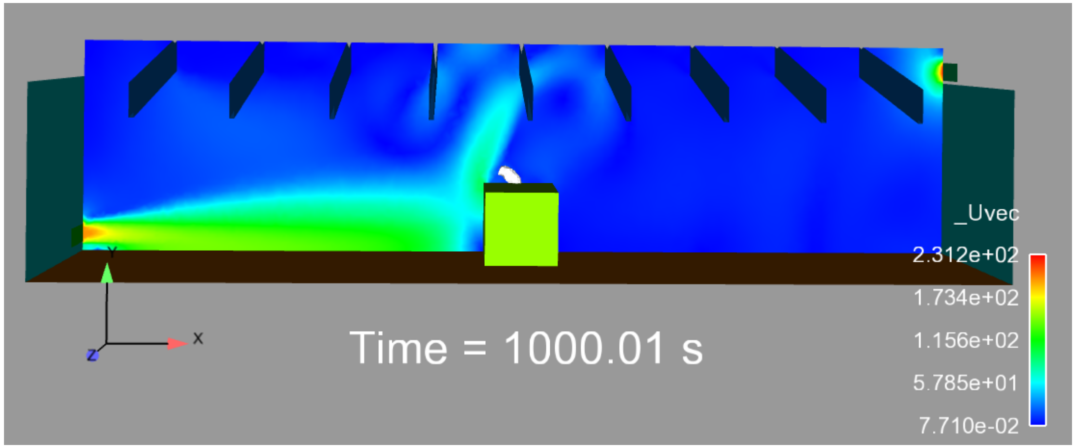
Natural Gas Vehicle Maintenance Garage

- Dimensions: 30.5 m x 15.2 m x 6.1 m; 1:6 roof pitch
- Layouts w/ and w/o horizontal support beams investigated:
  - 9 beams (15.2 x 107 cm^2) spaced 3.05 m & parallel to the roof pitch
- Two vents were used for air circulation
  - Inlet near the floor — outlet along roof of opposite side-wall
  - Vent area for both vents was 0.635 m x 3.32 m
  - Ventilation rate set to 5 air changes/hour (~2 m/s w/ current vent sizing)
  - Simulations were run with and without ventilation
- NGV modeled as a cuboid (2.44 m x 2.44 m x 7.31 m)



Simulations initialized with full ventilation until steady interior flow rates achieved

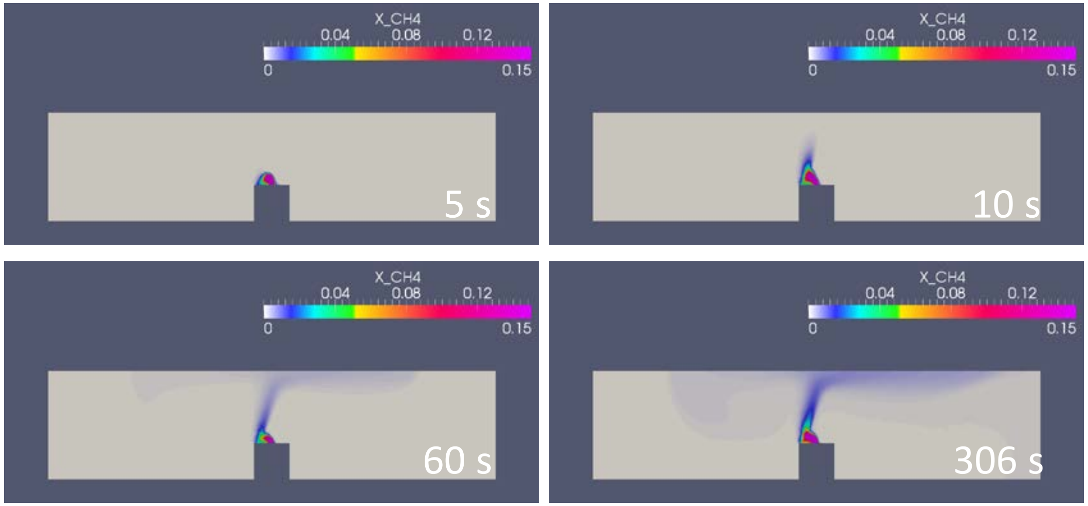




A low pressure recirculation region along the NGV left side results in plume distortion for certain conditions

Scenario 1: LNG Release

Constant release (7.6 g/s) of cool gas-phase NG (160 K) for 306 s

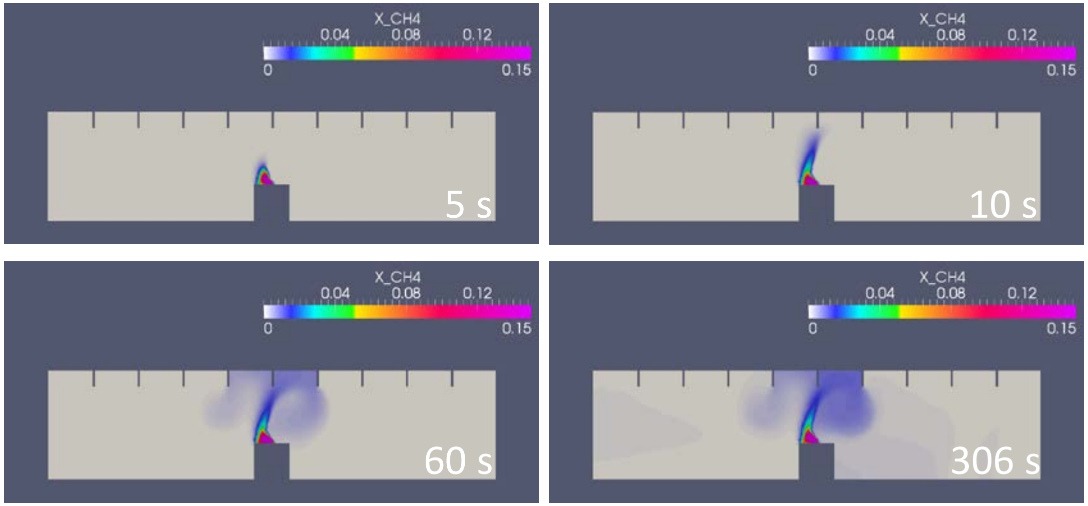


NGV facility w/o horizontal beams

- Distorted plume from vent currents
- Large cloud of overly-lean mixture spreads across the ceiling
- Only areas near NGV are flammable

NGV facility w/ horizontal beams

- Plume structure near NGV is similar to case w/o beams
- NG clouds are trapped in beam pockets but are not flammable



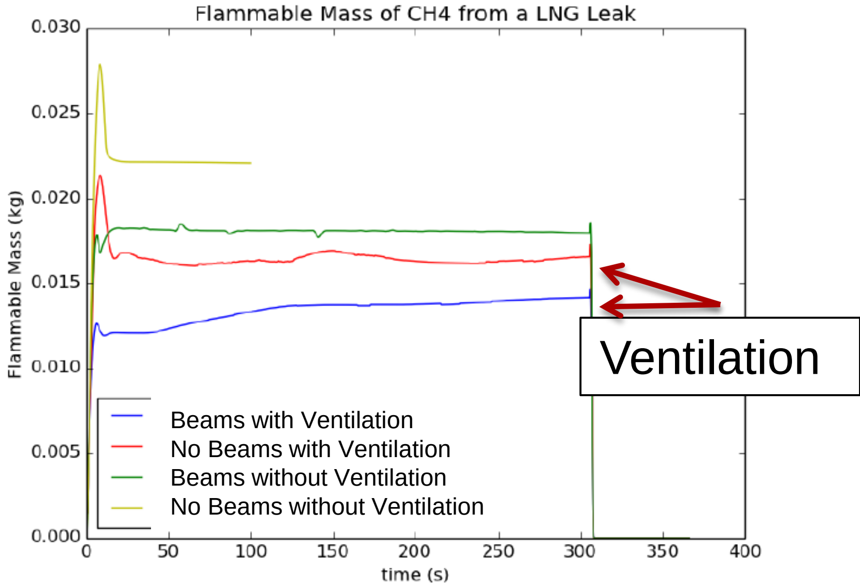
Flammable mass of NG can be used to determine potential facility overpressure hazard

Flammable mass : Cumulative fuel mass mixed into flammable concentrations (mixtures between 5% and 15% by volume for NG-air)

$$\Delta p = p_0 \left\{ \left[\frac{V_T + V_{NG}}{V_T} \frac{V_T + V_{stoich}(\sigma - 1)}{V_T} \right]^{\gamma} - 1 \right\}$$

C. R. Bauwens, S. Dorofeev, Proc. ICHS, 2013.

p_0: Ambient pressure
V_T: Facility volume
V_{NG}: Expanded volume of pure NG
V_{stoich}: Stoichiometric consumed NG volume
σ: Stoichiometric NG expansion ratio
γ: Air specific heat ratio (1.4)



Potential Consequences:

- 1 kPa: Breaks glass
- 6.9 kPa: Injuries due to projected missiles
- 13.8 kPa: Fatality from projection against obstacles
- 13.8 kPa: Eardrum rupture
- 15-20 kPa: Unreinforced concrete wall collapse

$$\Rightarrow \Delta p_{max} = 0.13\ kPa - 0.3\ kPa$$

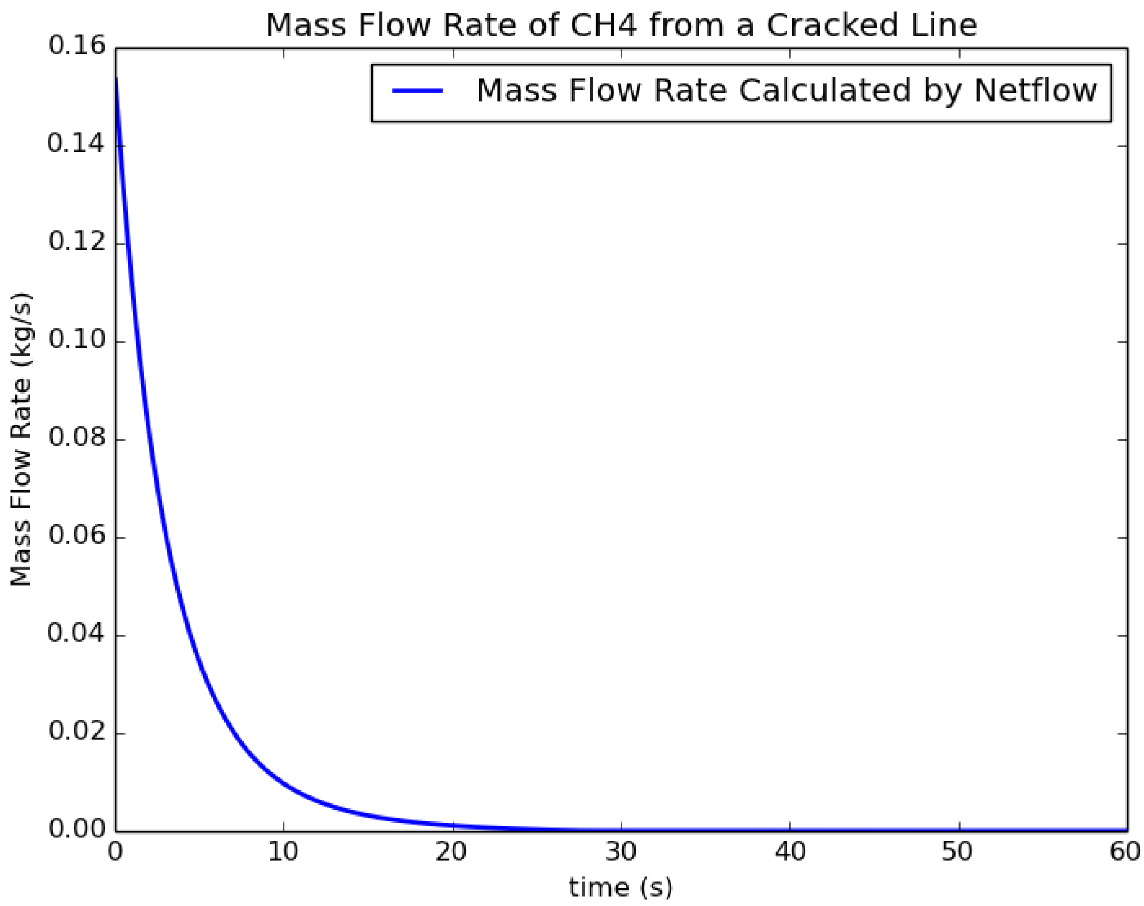
American Institute of Chemical Engineers, 1998.

No significant overpressure hazard for this hazard

— Local blast waves not considered

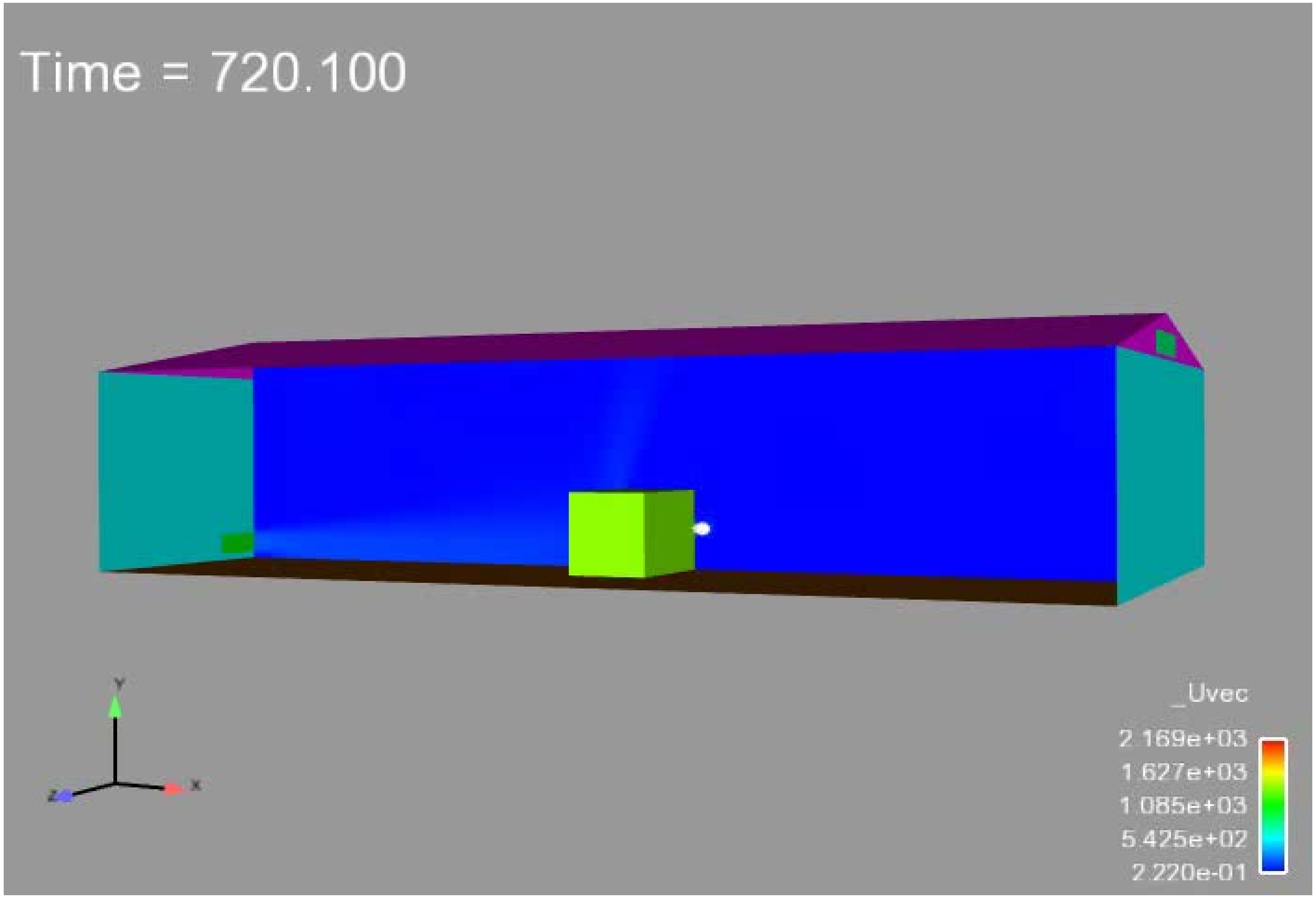
Scenario 3: CNG Fuel System Line Cracking

3.3 liters @ 248 bar; 3% area leak 1.27 cm ID tubing



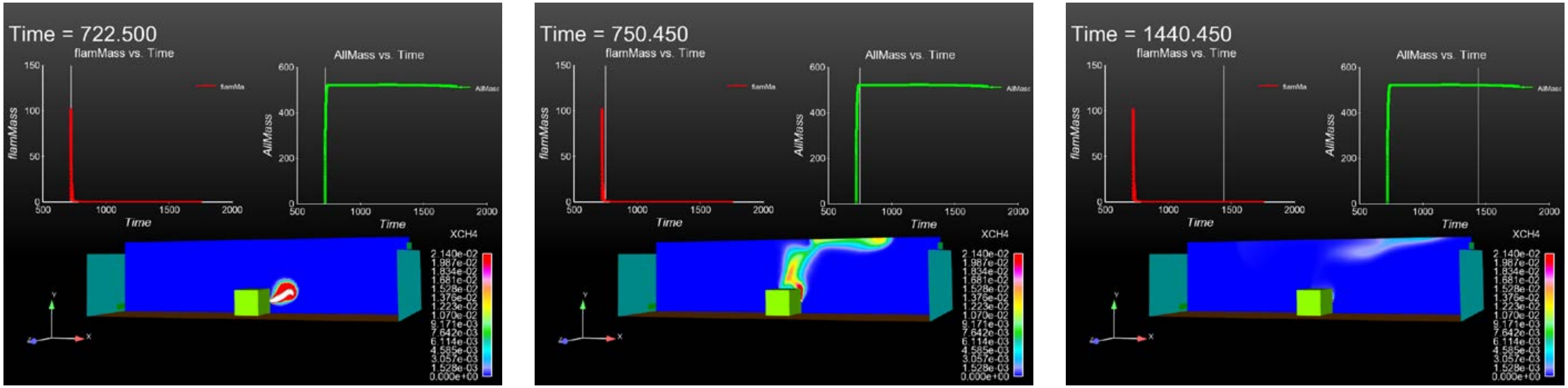
Play movie: Sideleak.avi

Scenario 3: CNG Vehicle Fuel System Line Cracking

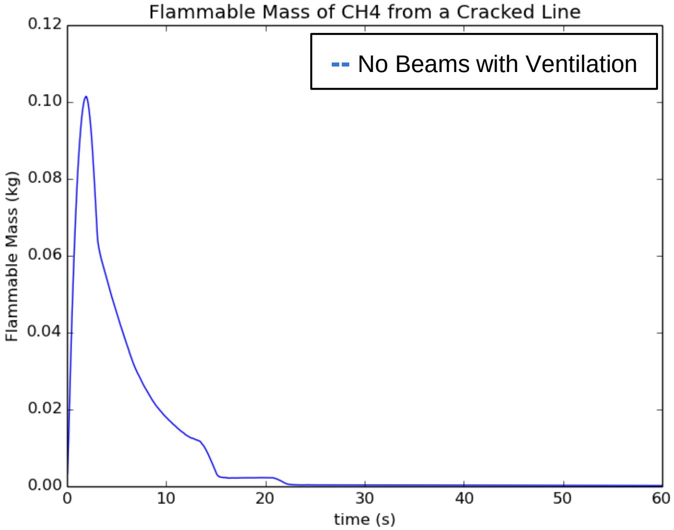


Scenario 3: CNG Fuel System Line Cracking

3.3 liters @ 248 bar; 3% area leak 1.27 cm ID tubing



$$\Delta p_{max,\ expansion} = 0.43\ kPa \text{ to } 1.3\ kPa$$



Potential Consequences:

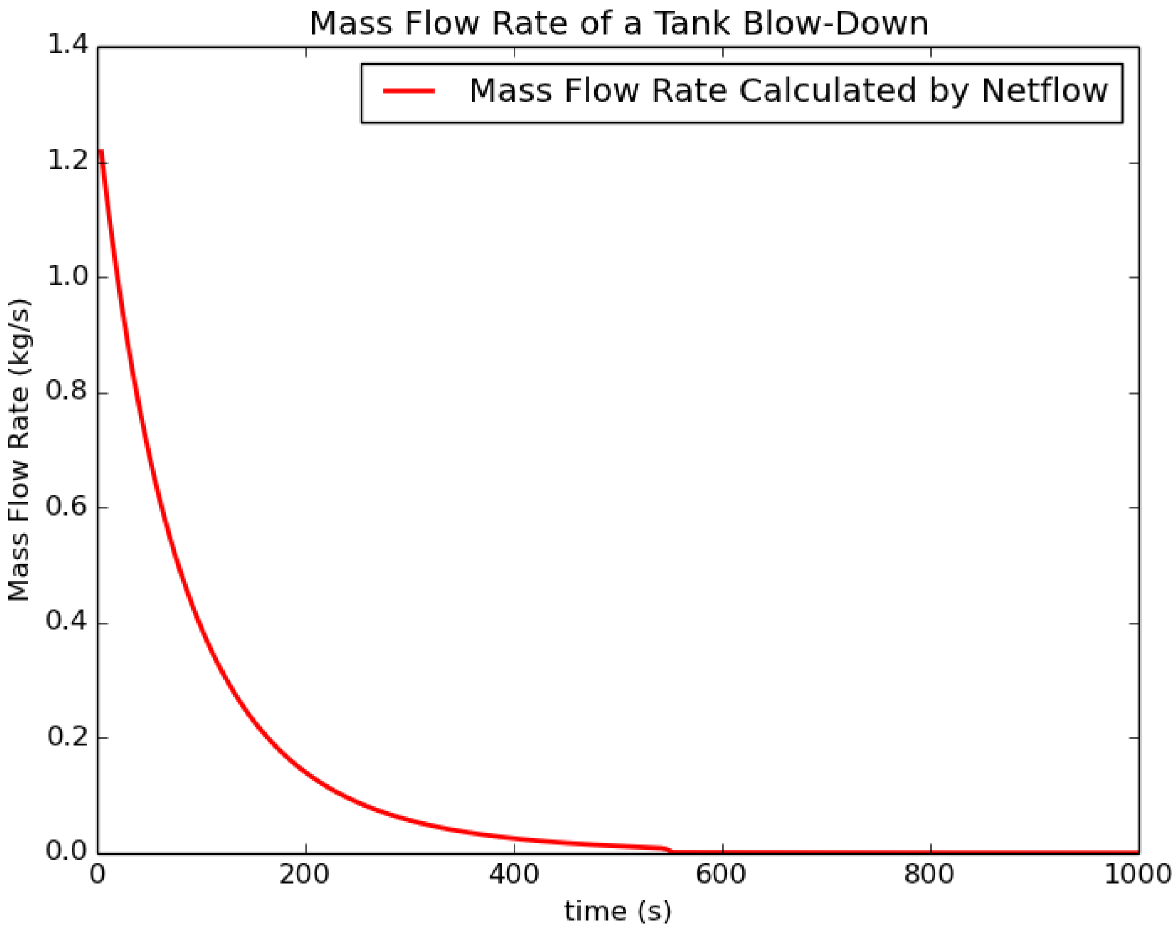
- 1 kPa: Threshold for glass breakage

American Institute of Chemical Engineers, 1998.

Again, no significant overpressure hazard for this hazard

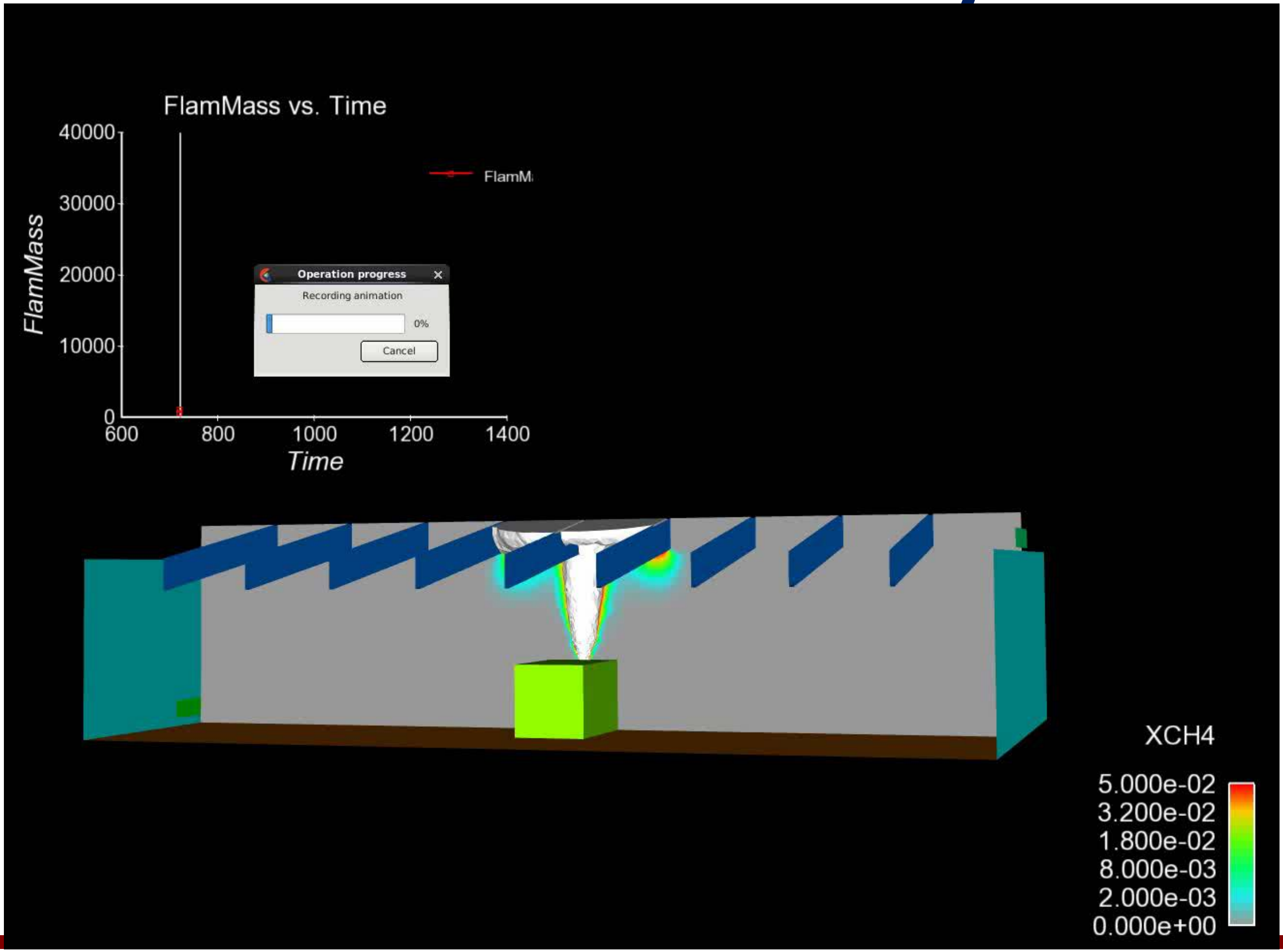
Scenario 4: Mechanical Failure PRD Release

0.7 m^3 volume @ 250 bar from a 6.2 mm PRD



Play movie: CNG_Blowdown.avi

Scenario 4: Mechanical Failure PRD Release - Preliminary



Observations

- Little sensitivity was observed for ventilation or roof supports due to the short durations of the releases relative to the ventilation rates and the propensity of the support structures to enhance mixing .
- For the low-flow release scenarios that involved a dormant LNG blow-off or a CNG fuel system purge, the flammable masses, volumes, and extents were low, and the flammable regions disappeared shortly after the conclusion of the leaks. Moreover, predicted peak overpressures indicated there was no significant hazard expected.
- For the larger release, the release plume quickly achieved a nearly steady flammable volume that extended from the release point at the vehicle up to the ceiling, before spreading across the ceiling.
- No attempt to calculate local blast-wave pressures was performed, which could result in additional overpressures above those described here. However, for the low release cases, the relatively small volumes of the flammable regions mean that there is little opportunity for flame acceleration needed for blast-wave development.

NFPA 30A-Section No. 8.2.1

- In major repair garages where CNG vehicles are repaired or stored, the area within 455 mm (18in.) of the ceiling shall be designated a Class I, Division 2 hazardous (classified) location.
- *Exception: In major repair garages, where ventilation equal to not less than four air changes per hour is provided, this requirement shall not apply.*
- *Proposing to remove this section.*

Plans for Phase II

- Re-assess Case #4
- Development of multi-phase flow simulation capabilities
- Refine Risk Assessment from Phase I

- Open to suggestions…
  - This year and future years

NFPA 2 LH2 Separation Distance Task Group

NFPA 2 LH2 Separation Distance Task Group

- Methodology
  - Began with the CGA P-28 document on Liquefied Hydrogen System which included a HAZOP for a “typical” system
  - PHAWorks software was used to capture the risk matrix values assigned to each credible scenario for frequency and severity
  - Risk prioritization output 9 scenarios of concern that the task group felt should be used to determine separation distances

Assumptions

- Code compliant system - NFPA 55, CGA H-5
- Single failure - no cascading failures
- Single system
- Safety measures function properly on demand
- Current setback distances provide no credit in this study
- In natural disaster consideration, tornadoes are not included

Nodes

- Node 1 Delivery hose and trailer
- Node 2 Storage
- Node 4 Hydrogen line
- Node 6 Tank vent stacks

Modeling Scenarios for LH2 System

- Node (1)1.18 High flow from trailer vent stack
- Node (1) 1.19 Normal hydrogen flow from trailer vent stack
- Node (1) 1.6 High Flow- Line rupture valve or component failure
- Node (4) 4.15 Loss of containment-caused by thermal cycles or ice falling from vaporizers
- Node (6) 6.15 misdirected flow- caused by operator error resulting in large low level release

Modeling Scenarios for LH2 System

- Node (1)-1.4 High temperature caused by external fire
- Node (1)-1.8 reverse flow
- Node (1) 1.16 Loss of containment -External impacts etc- consider all causes
- Node (2) 2.1 High pressure- leak in inner vessel

Next Steps

- Each scenario will be modeled to determine extent of the hydrogen concentration, temperature, heat flux (if ignited)
- The hydrogen exposure risk criteria for each of these will be used to determine the appropriate separation distance for specific exposure such as air intakes, ignition sources, etc.