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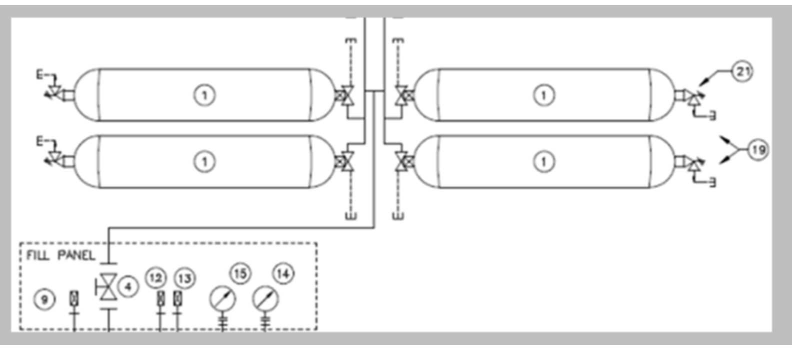

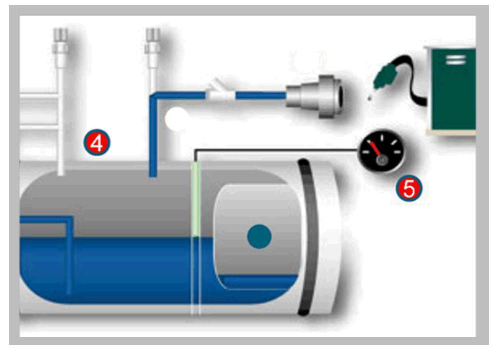

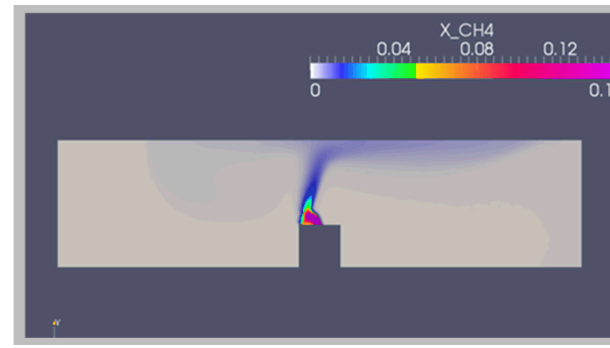

Risk-Informed LNG/CNG Maintenance Facility Codes and Standards

Project sponsored by Clean Cities:

Technical & Analytical Assistance

Myra Blaylock

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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SAND NO. 2015-7361PE

Team Members

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- Rad Bozinoski
- Ethan Hecht
- Amanda Dodd

- Doug Horne

Talk Objectives

- Review SNL work – HAZOP and Modeling
  - Review of Phase I (2014)
  - Update of Phase II (2016)

- Get feedback from NGVAmerica for next year's focus

- New website: altfuels.sandia.gov

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

Phase II

Phase III

- 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
- Development of best practices to mitigate hazards
- Additional CFD Modeling
- Propose changes to existing fire protection codes

- note: published by CVEF -> NGVAmerica

http://www.ngvamerica.org/media-center/technical-and-safety-documents/

Codes & Standards

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.

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.*

IFC 2311.7.1

- **2015 International Fire Code**
- **2311.7.1 Ventilation.** Repair garages used for the repair of natural gas- or hydrogen-fueled vehicles shall be provided with an *approved* mechanical ventilation system. The mechanical ventilation system shall be in accordance with the *International Mechanical Code* and Sections
- 2311.7.1.1 and 2311.7.1.2.
- **Exception:** Repair garages with natural ventilation when *approved*.
- **Exception**: Natural gas vehicle repair garages meeting existing ventilation rates shall not be required to be updated with a mechanical ventilation system.

HAZOP and Recommendations

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	Consequence	Design	Ad-min	Detection Method	Design	Admin	Prob. Class	Consequence Class	Risk Priority
CNG-3 (Pressure Relief Device fails open)	Mechan-ical defect, material defect, installa-tion error, mainten-ance error	Potential catastrophic release of CNG	Use improved PRD design		Gas indicator alarm	Improved PRD is more reliable	Prioritize parking of dead vehicles outdoors	Low	2	Low

Assumptions

- Activities

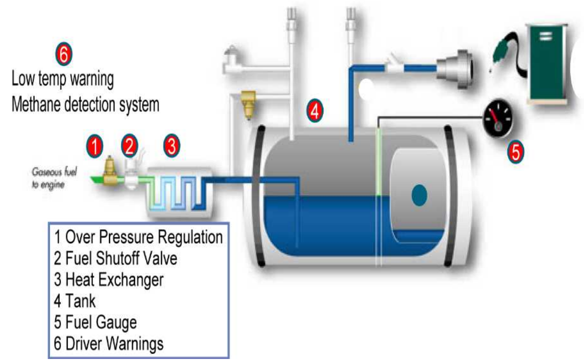
Service Maintenance and Repair Activities
Inspection of fuel storage and delivery piping, components (including PRD)
Inspection of fuel safety systems
Troubleshoot/ Testing
Exchange filters
Drain and replace fluids (non fuel system)
Replace non fuel system component (brakes, tires, transmission, etc.)
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 Structure

Sandia National Laboratories

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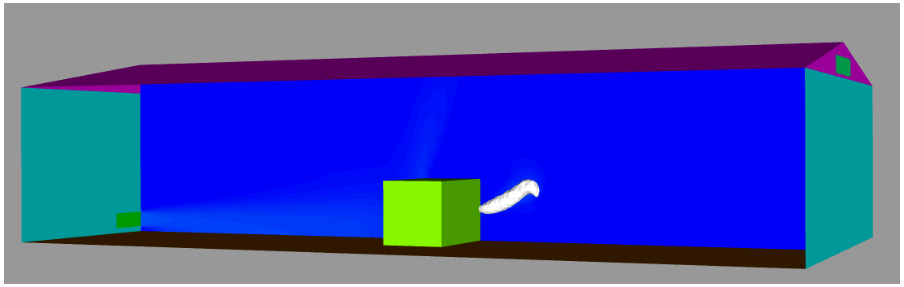
HAZOP Results

- Scenarios Selected for Modeling (Phase I)
  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 TPRD.

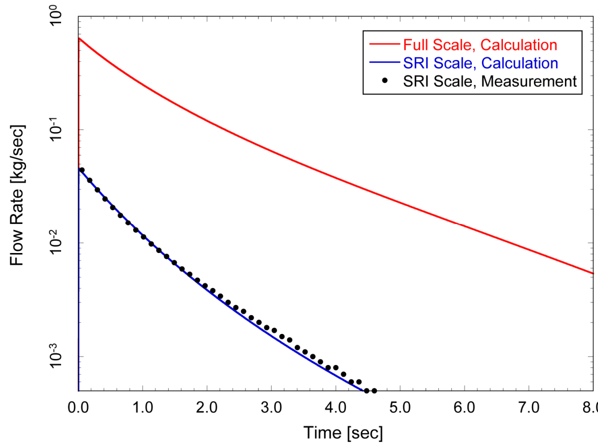


HAZOP Results: New Scenarios to be Modeled

1. CNG- Tubing
   - Leakage from tubing downstream of isolation valve .
   - Model smaller facility for Light Duty vehicles.
2. CNG - Cylinder
   - Outlet or fitting on tank fails due to manufacturing defect or installation or maintenance error. Entire contents of CNG cylinder.
   - Model smaller facility for Light Duty vehicles.
3. LNG – Heat exchanger
   - Leaks of LNG or GNG due to defective materials, corrosion, thermal fatigue, pressure rupture, etc.
   - Potential Multi-Phase Flow
4. LNG – Cylinder
   - Total volume of tank released due to pressure valve release– slower than with CNG = could affect sensor and ventilation requirements.
   - Potential Multi-Phase Flow

Modeling and Simulations

Simulation Methodology

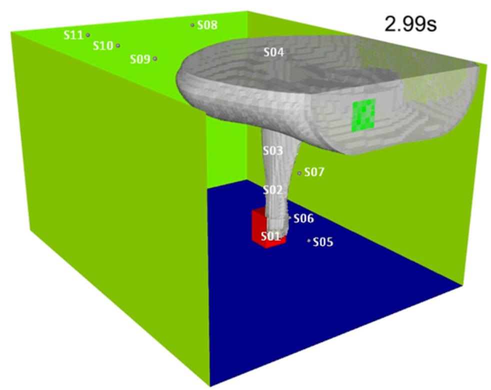


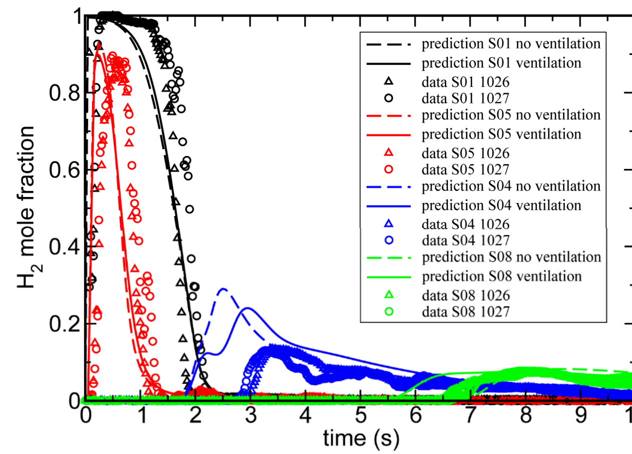
Blowdown release rates calculated via Sandia network flow solver (NETFLOW)

Winters, SAND Report 2009-6838.

Sandia FUEGO flow solver

- Finite volume
- Compressible Navier-Stokes
- k-ε turbulence model
- Slip isothermal walls (294 K)
- ~10 cm mesh spacing



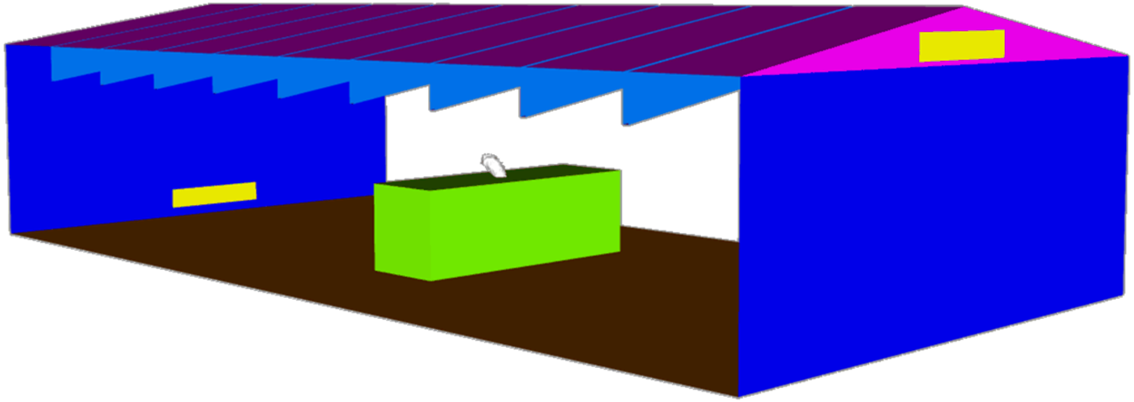


Houf et al., Int J H2Energy, 2013.

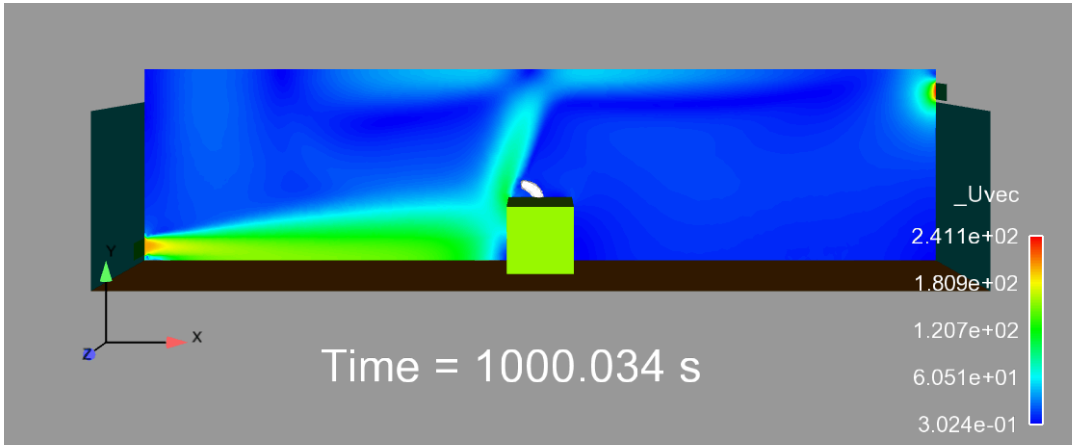
Methodology previously validated against large-scale hydrogen blowdown release experiments

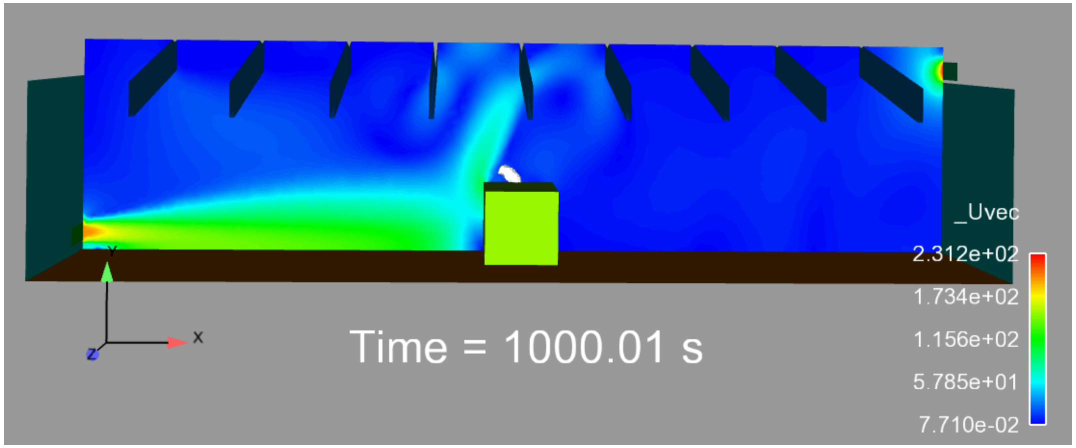
Natural Gas Vehicle Maintenance Garage

- Dimensions: 100’ x 50’ m x 20’ m; 1:6 roof pitch
- Layouts w/ and w/o horizontal support beams investigated:
  - 9 beams (6” x 42”) spaced 10’ & 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 2’ x 10’
  - 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 (8’ x 8’ x 24’)



Simulations initialized with full ventilation until steady interior flow rates achieved

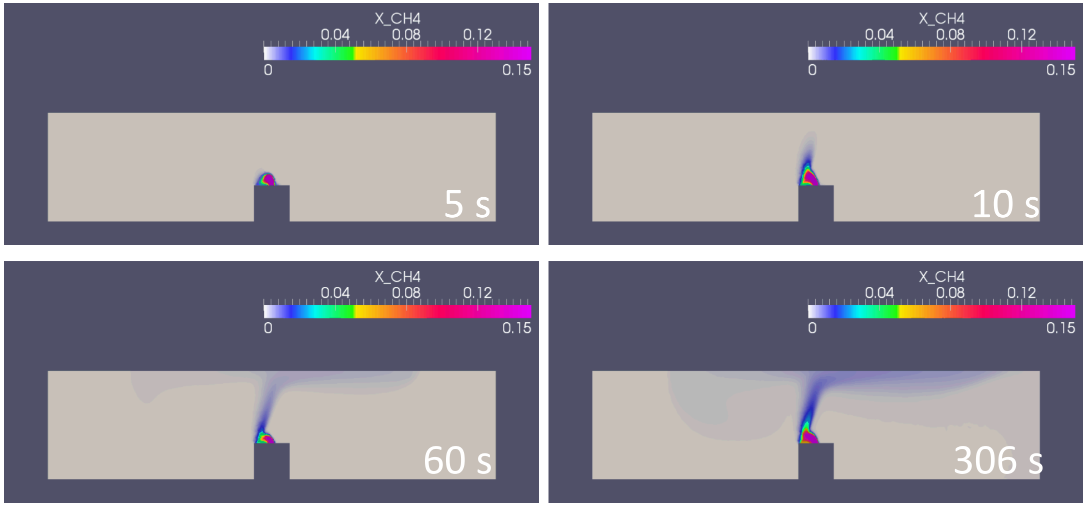




A low pressure recirculation region along the NGV left side results in plume distortion for certain conditions

Scenario 1: LNG Release

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

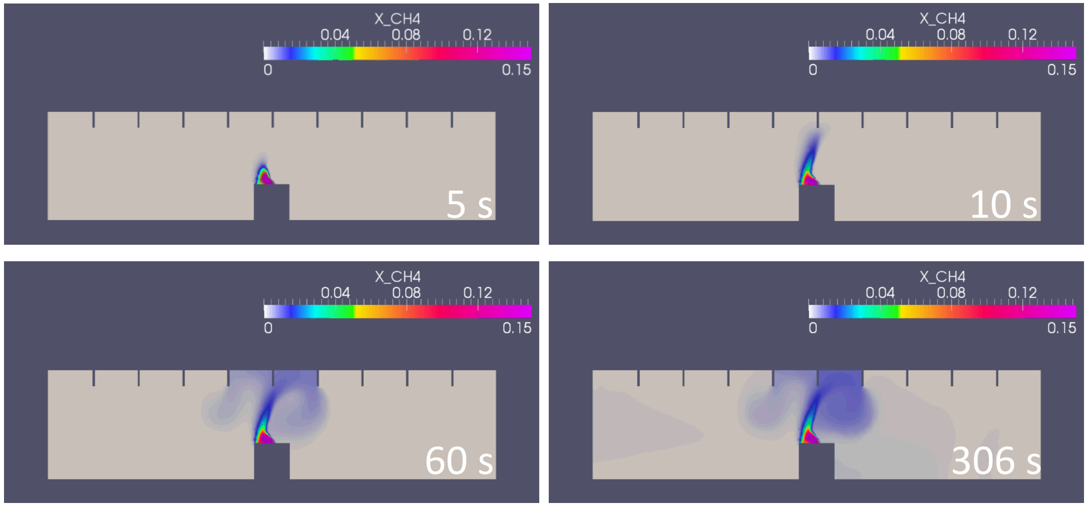


NGV facility w/o horizontal beams

- 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



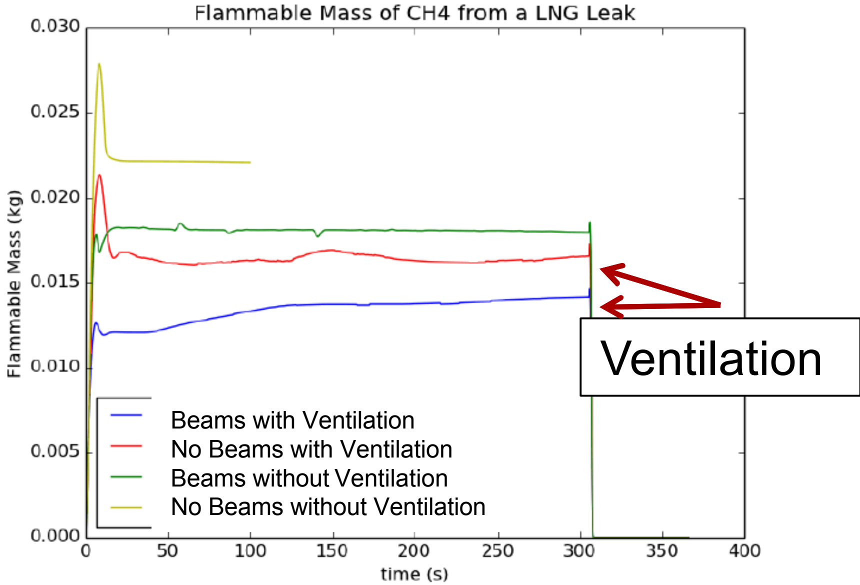
Flammable mass of NG can be used to determine potential facility overpressure hazard

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

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

American Institute of Chemical Engineers, 1998.

No significant overpressure hazard for this hazard

— Local blast waves not considered

Best Practices Example: LNG "Burping"

- Release Prevention Features
  - Design
  - Administrative
- Release Detection Method
- Release Mitigation Features
  - Design
  - Administrative

- Ignition Prevention Features
  - Design
  - Administrative
- Ignition Detection Method
- Ignition Mitigation Features
  - Design
  - Administrative

Best Practices Example: LNG "Burping"

- Release Prevention Features
  - Design
  - Administrative
- Release Detection Method
- Release Mitigation Features
  - Design
  - Administrative
- Ignition Prevention Features
  - Design
  - Administrative
- Ignition Detection Method
- Ignition Mitigation Features
  - Design
  - Administrative

Release Prevention Features	
Design	Administrative
1 -Regulator Approved for LNG - cold vapor 2 -Compatible materials for cryo temperatures	2 -Preventative Maintenance 3 -Acceptance Test/ Construction Quality 6 -Operator Training - hold times

Best Practices Example: LNG "Burping"

- Release Prevention Features
  - Design
  - Administrative
- Release Detection Method
- Release Mitigation Features
  - Design
  - Administrative
- Ignition Prevention Features
  - Design
  - Administrative
- Ignition Detection Method
- Ignition Mitigation Features
  - Design
  - Administrative

Release Detection Method
3 -Hear hissing sound, 4 -Pressure gauges - in vehicle 6 -See visible cloud 9 -Low temperature warning - in vehicle detector (for operation state 4, 5, 7 person detects)

Best Practices Example: LNG "Burping"

- Release Prevention Features
  - Design
  - Administrative
- Release Detection Method
- Release Mitigation Features
  - Design
  - Administrative
- Ignition Prevention Features
  - Design
  - Administrative
- Ignition Detection Method
- Ignition Mitigation Features
  - Design
  - Administrative

Release Mitigation Features	
Design	Administrative
6 -Relief Device or manual release of pressure to atmosphere	Optional Operating Procedures - attach flex vent hose to relief valve; turn on ventilation; open doors

Best Practices Example: LNG "Burping"

- Release Prevention Features
  - Design
  - Administrative
- Release Detection Method
- Release Mitigation Features
  - Design
  - Administrative
- Ignition Prevention Features
  - Design
  - Administrative
- Ignition Detection Method
- Ignition Mitigation Features
  - Design
  - Administrative

Ignition Prevention Features	
Design	Administrative
1 -Electrical classification areas - over vehicle (e.g. lights) 2 -Grounding & bonding of vehicle in bay	3 - Prohibit smoking

Best Practices Example: LNG "Burping"

- Release Prevention Features
  - Design
  - Administrative
- Release Detection Method
- Release Mitigation Features
  - Design
  - Administrative
- Ignition Prevention Features
  - Design
  - Administrative
- Ignition Detection Method
- Ignition Mitigation Features
  - Design
  - Administrative

Ignition Detection Method
1 -Gas detection (LEL sensor) (location TBD depending upon modeling, may delete, if not effective) 2 -Fire alarm (heat / smoke) detection 3 - Person smelling smoke 4 - Visual flame

Best Practices Example: LNG "Burping"

- Release Prevention Features
  - Design
  - Administrative
- Release Detection Method
- Release Mitigation Features
  - Design
  - Administrative
- Ignition Prevention Features
  - Design
  - Administrative
- Ignition Detection Method
- Ignition Mitigation Features
  - Design
  - Administrative

Ignition Mitigation Features	
Design	Administrative
3 - Automatic fire suppression 5 - Separation distance to exposures (distance TBD based on modeling)	2 - Operating procedures 2 - Portable fire extinguisher

Best Practices Example: LNG "Burping"

- HAZOP Scenario # 7, LNG Relieve Valve Activating due to Overpressure of Tank
-
- HAZOP scenario 7 is external leakage of LNG from the regulator body, due to over pressurization caused by the warming of the tank when the vehicle is parked for an extended period of time. This will result in a minor leakage of gaseous natural gas (GNG), which is a low consequence. This scenario is expected to occur.
-
- Releases of this type are reduced by using a regulator that is approved for LNG, where the cold vapor temperatures are key. Administrative controls that can reduce this scenario include preventative maintenance, acceptance testing, quality construction, operator training and leak testing. Operator training would include activities such as regulator maintenance, installation procedures, and leak testing of regulators when they are installed. Methods for detecting a release include both in vehicle and facility indicators and human senses. LNG vehicles have both a gas detection system and low temperature warning in the vehicle cab to alert workers. The facility system has a sensor to detect value failure. Operators in the area may be able to hear a hissing sound as gas leaks from the regulator, see a visible vapor cloud as the cold gas is released or read a pressure gauge and note pressure dropping. Each of these should be covered in operating procedures, operator training and the operator's response to these indications. Mitigation of the release for the regulator can occur with design features such as an automatic shut off valve, pressure relief device or manual release of pressure to the atmosphere.
-
- Facility features that can prevent ignition of released LNG include grounding and bonding of the vehicle when it is brought into the maintenance bay. Administrative controls that can prevent ignition of the small LNG release include operating procedures, general housekeeping, in particular limitations on combustible materials and keeping floors clean of oil and grease, and combustible trash in covered metal containers and prohibition of smoking. In addition, based on the modeling, an administrative control on limiting heat-producing appliances, such as ceiling lights and heaters, above the maintenance areas can prevent ignition of the released LNG. Detection of ignition can be by fire alarm or a person smelling smoke or seeing a visual flame. Mitigating the fire is addressed by operating procedures, including response to a fire and portable fire extinguishers.
-
- The HAZOP scenario, release prevention and mitigation, and ignition prevention and mitigation features are summarized in the tables below.
-

Best Practices Example: LNG "Burping"

HAZOP Number	Component	Operation State	Hazard Scenario	Causes	Consequences
1	LNG-1 (Overpressure regulator)	4, 8	External leakage from regulator body	Seal failure, mechanical defect, damage, etc.	Minor leakage of GNG

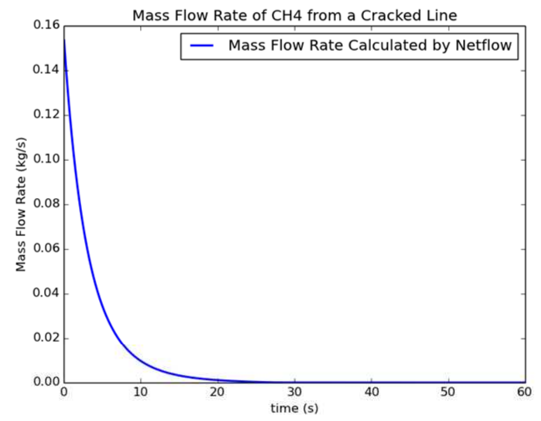
Release Prevention Features			Release Mitigation Features	
Design	Administrative	Release Detection Method	Design	Administrative
1 -Regulator Approved for LNG - cold vapor	2 -Preventative Maintenance 3 -Acceptance Test/ Construction Quality 6 -Operator Training (Maintenance; Installation & leak testing of new installations) 8 -Leak Testing	1-Gas Detection in vehicle, 3 -Hear hissing sound, 4 -Pressure gauges 6 -See visible cloud 8 -Facility sensor to detect failure of any valves 9 -Low temperature warning in cab	1 -Auto shutoff valve 6 -Relief Device or manual release of pressure to atmosphere	Operating Procedures - response to release detection

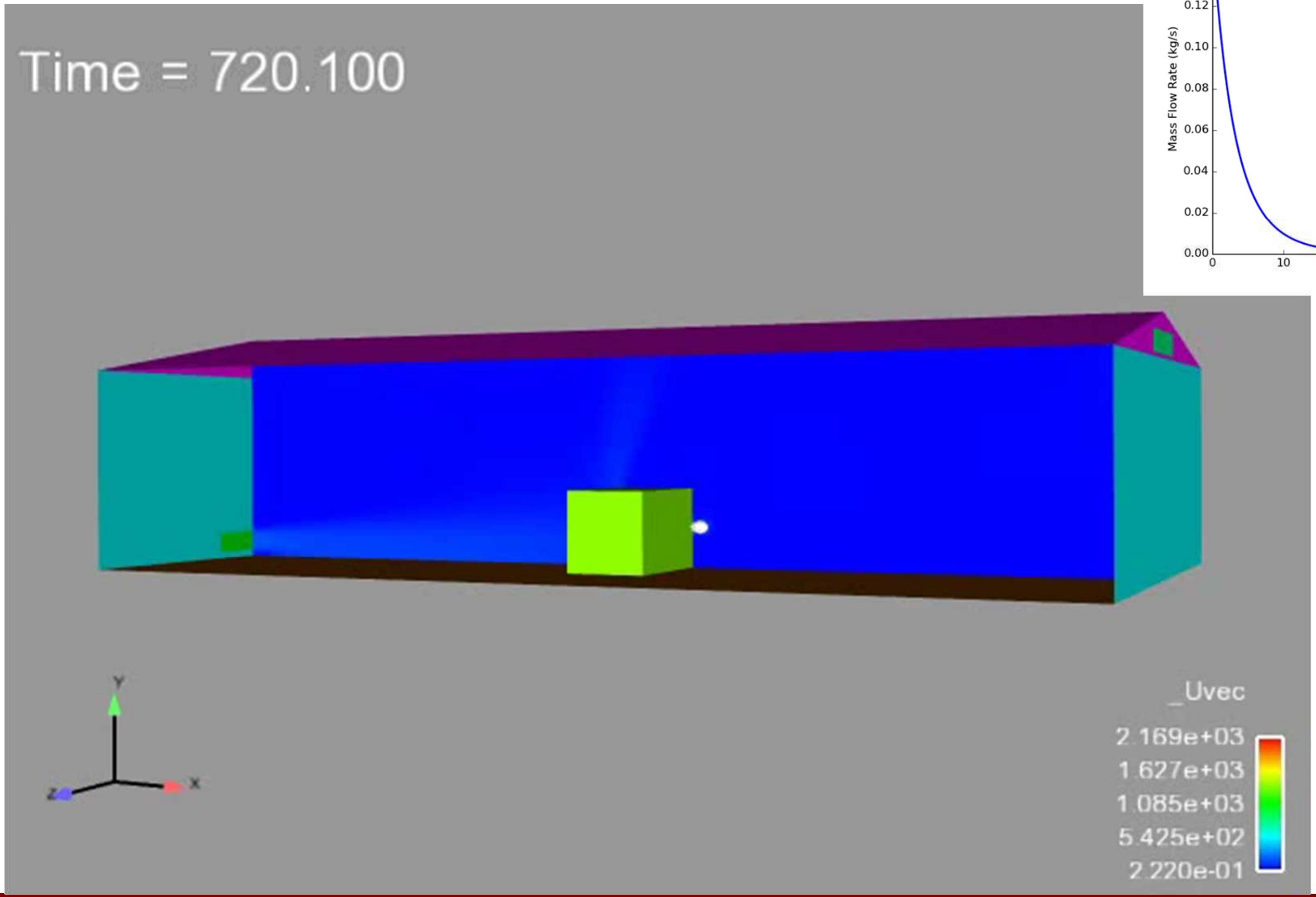
Ignition Prevention Features			Ignition Mitigation Features	
Design	Administrative	Ignition Detection Method	Design	Administrative
2 -Grounding & bonding of vehicle in bay	1 -Operating procedures 2 -Housekeeping (combustible material limitations) 3 - Prohibit smoking 5 -Floors kept clean of oil & grease 6 - Combustible trash in covered, metal receptacles 7 - Limit heat-producing appliances (ceiling lights & heaters)	2 -Fire alarm detection 3 - Person smelling smoke 4 - Visual flame	-	1 - Operating procedures - response to a fire 2 - Portable fire extinguisher

9 -Low temperature warning in cab (What is it sensing & what actions are taken - LNG slide 6)
1 -Auto shutoff valve (LNG slide of #2 fuel shut off valve)

Scenario 3: CNG Vehicle Fuel System Line Cracking: 3.3 liters @ 248 bar; 3% area leak

1.27 cm ID tubing





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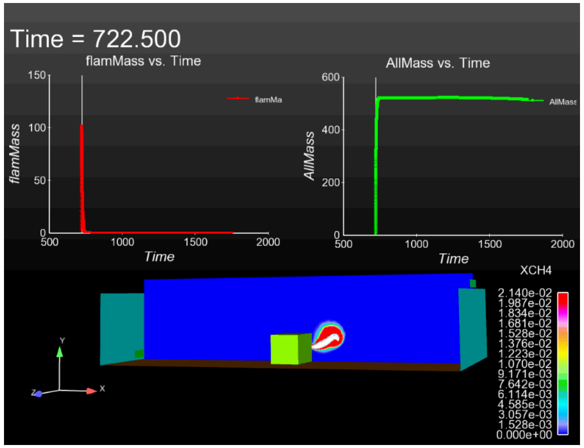
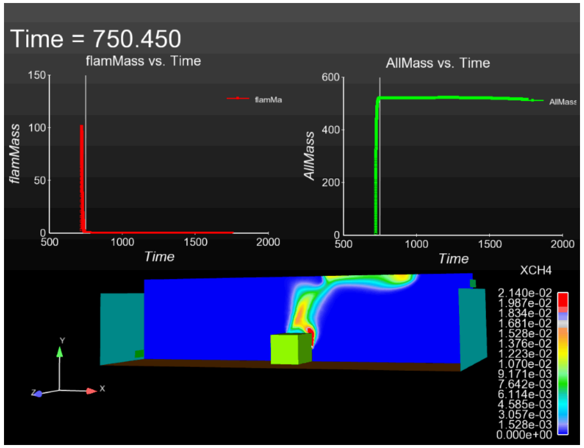
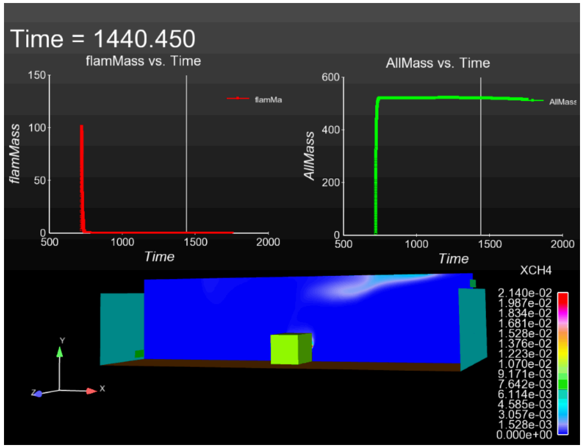
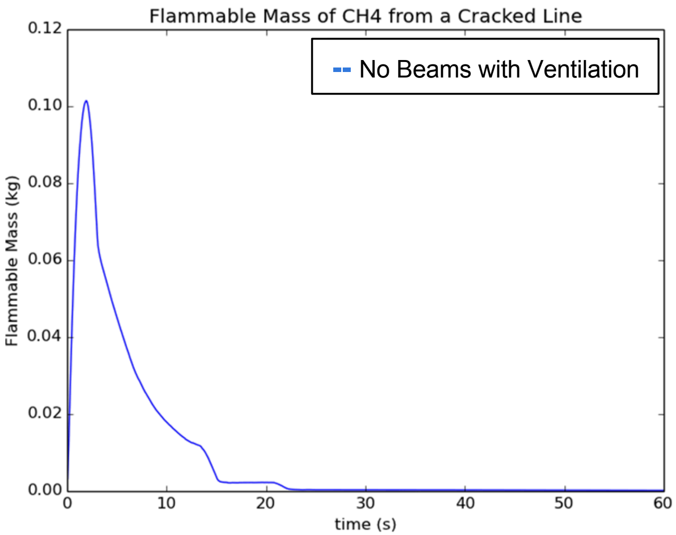






$$\Delta p_{max,\ expansion} = 0.43\ kPa \text{ to } 1.3\ kPa$$



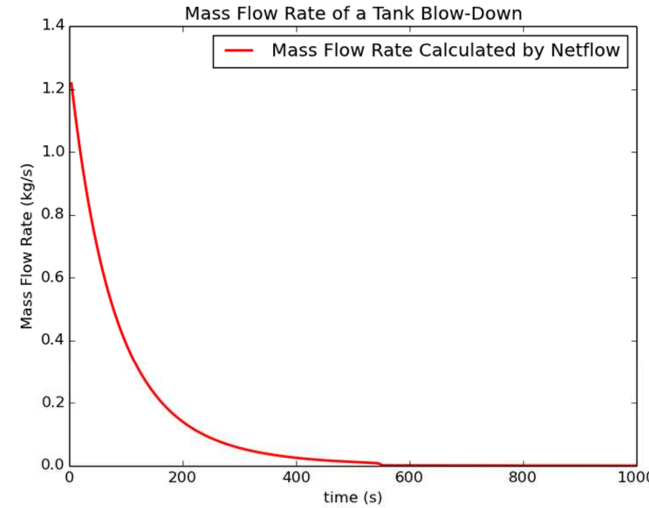
Potential Consequences:

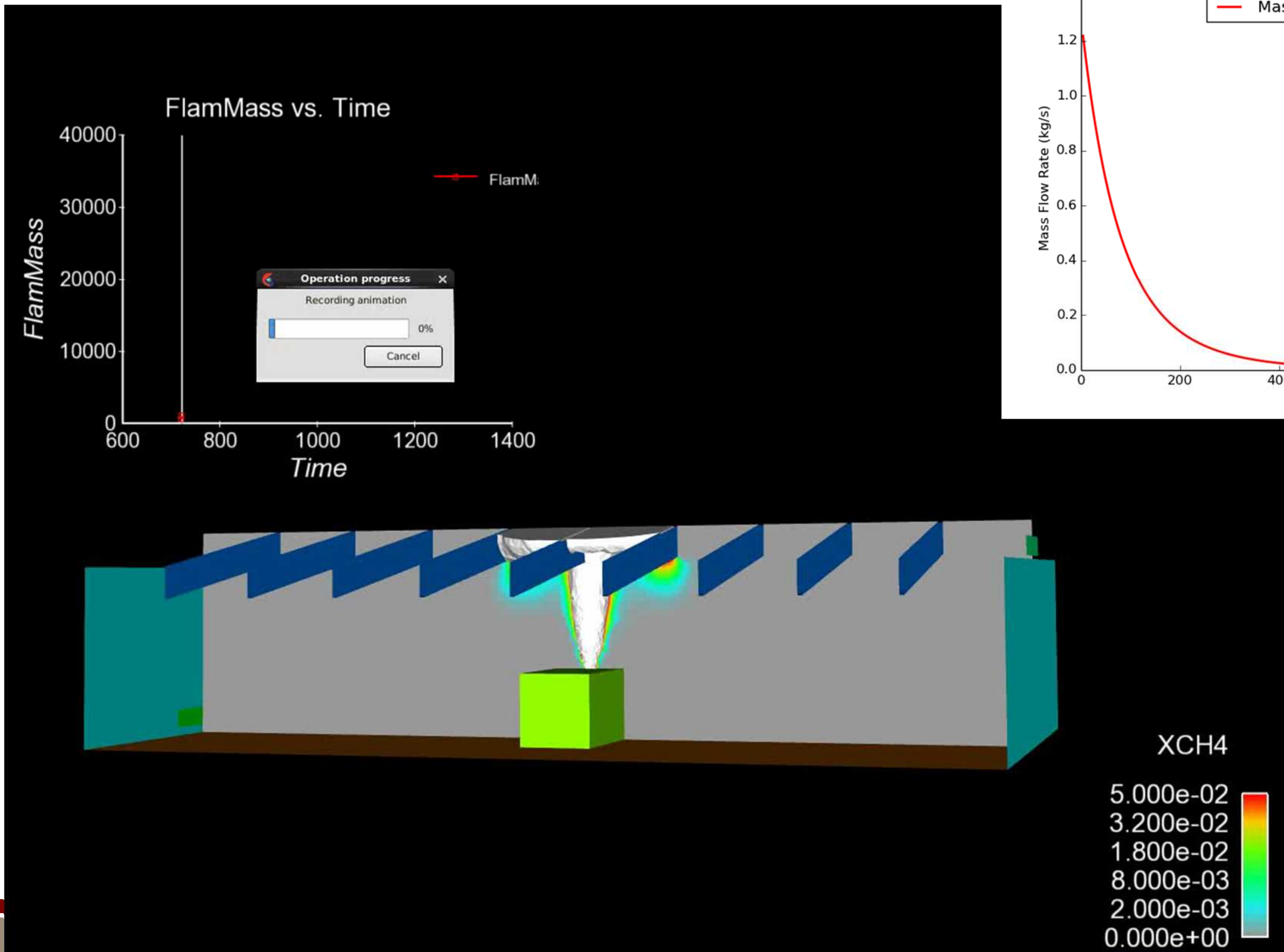
- 1 kPa: Threshold for glass breakage

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 TPRD





$$\Delta p_{max\ expansion} = 220\ kPa$$

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 .
  - **IFC 2311.7.1**
- 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.
  - **NFPA 30A**
- 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.

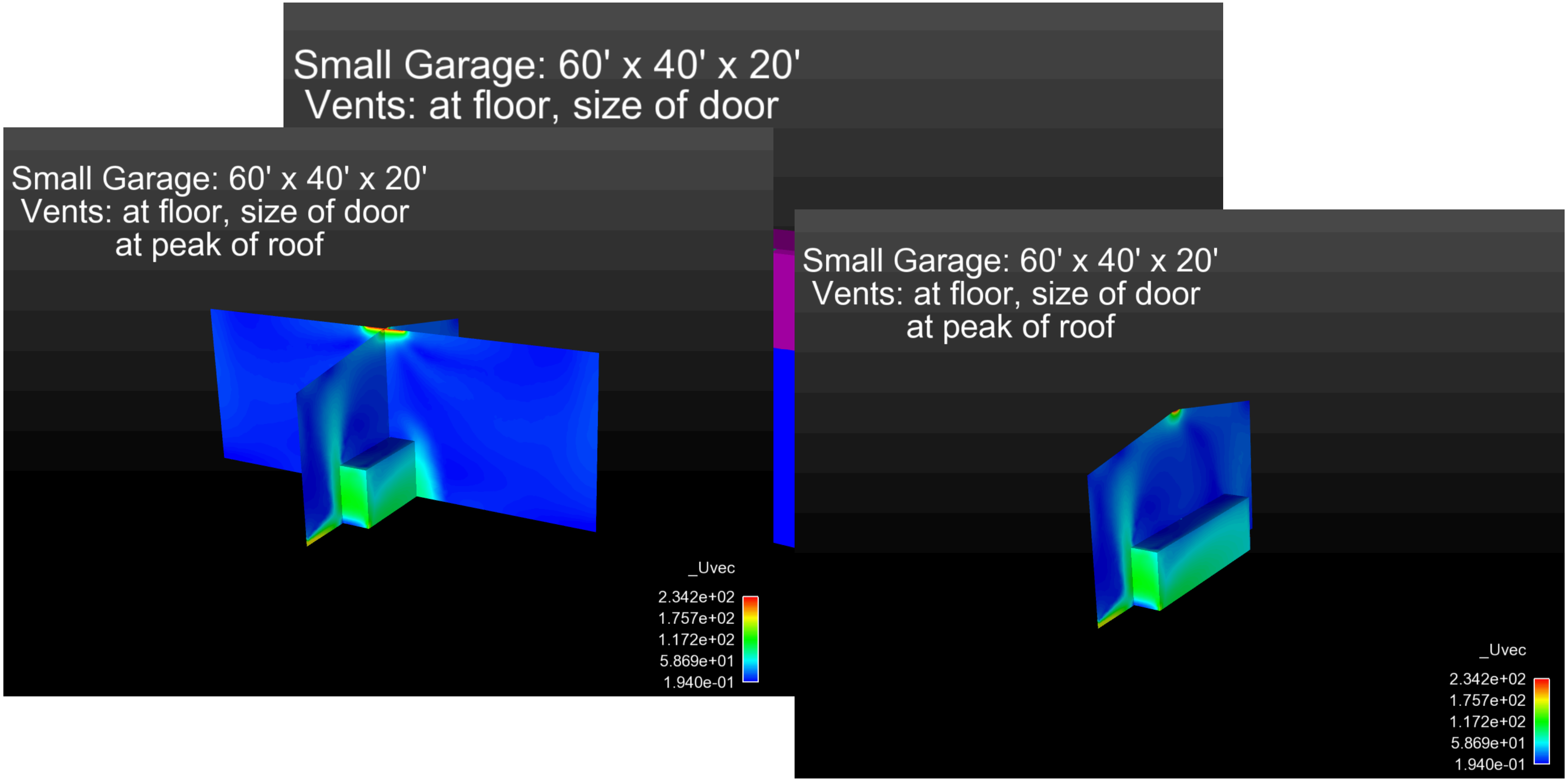
New Modeling and Simulations

HAZOP Results: New Scenarios to be Modeled

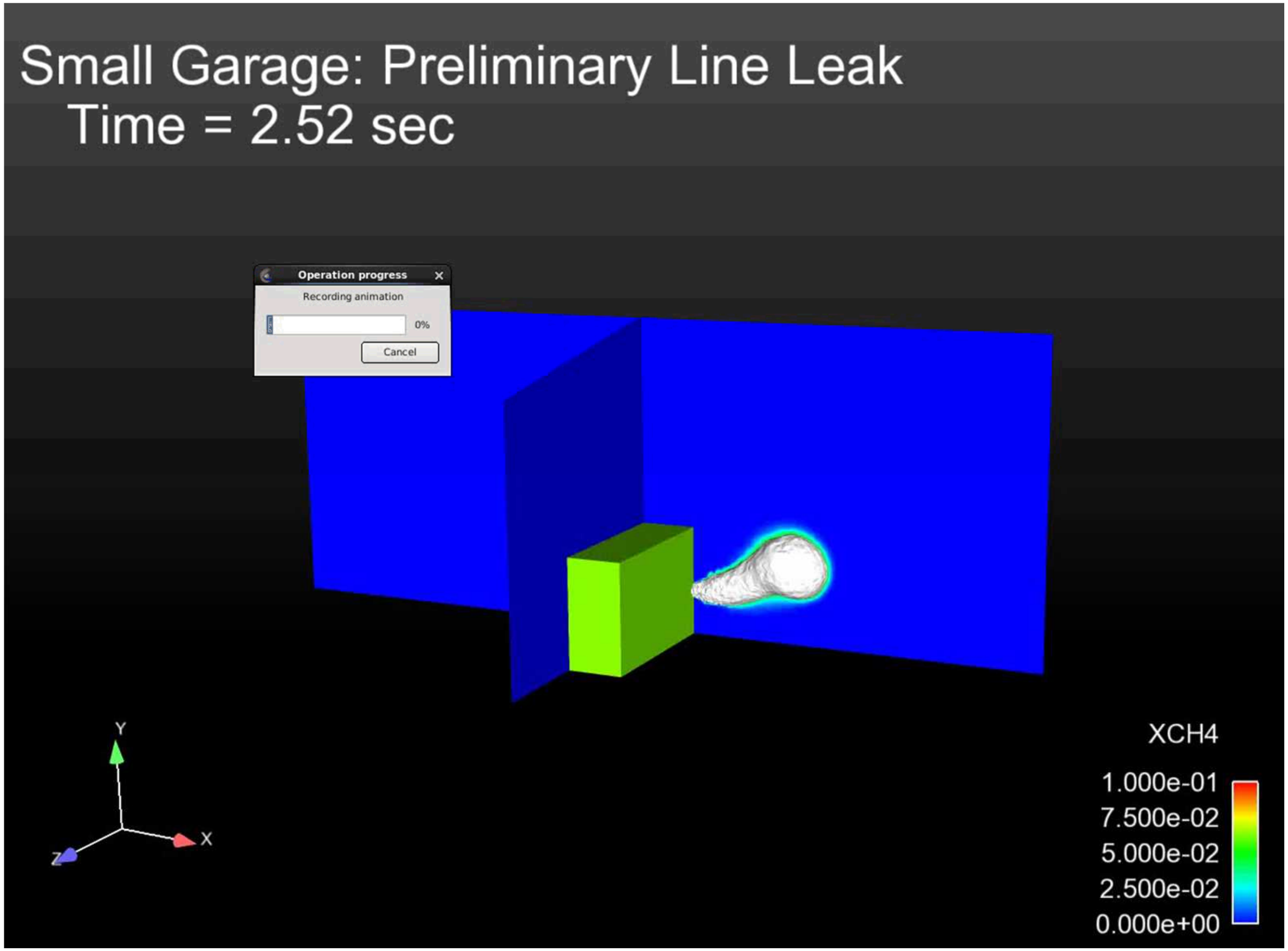
1. CNG- Pipes/Tubing
   - Leakage from tubing downstream of isolation valve .
   - Model smaller facility for Light Duty vehicles. 60’ x 40’ 20’
2. CNG - Cylinder
   - Outlet or fitting on tank fails due to manufacturing defect or installation or maintenance error. Entire contents of CNG cylinder.
   - Model smaller facility for Light Duty vehicles.
3. LNG – Heat exchanger
   - Leaks of LNG or GNG due to defective materials, corrosion, thermal fatigue, pressure rupture, etc.
   - Potential Multi-Phase Flow
4. LNG – Cylinder
   - Total volume of tank released due to pressure valve release– slower than with CNG = could affect sensor and ventilation requirements.
   - Potential Multi-Phase Flow

Small Garage Preliminary Results: Ventilation

- 5 ACH: Through door and peak of roof



Small Garage Preliminary Results: CNG Leak from Pipes

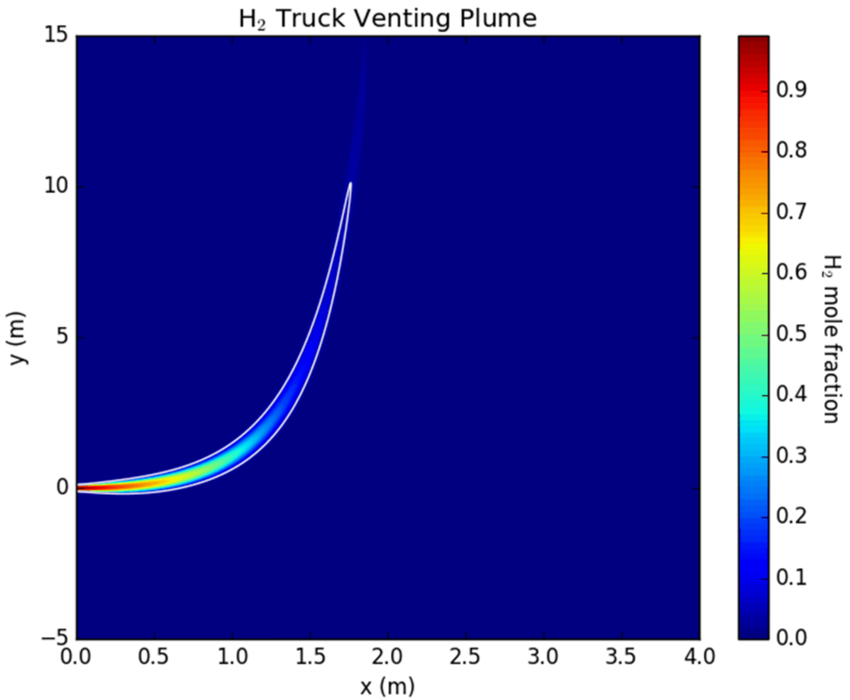


Small Garage Preliminary Results: CNG Leak from Pipes with Ventilation

- (movie added if available)

"Cold Plume" Capabilities For LNG

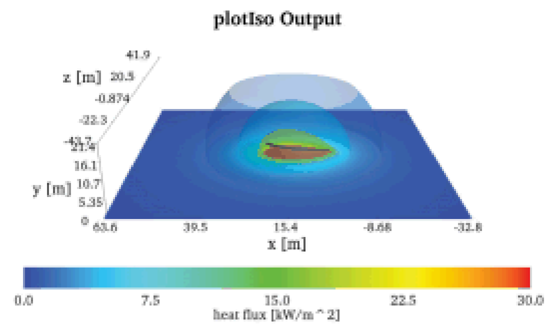
- Leaks from a two-phase container are possible
  - From the top: gaseous region
  - From the bottom: liquid region
- Two phase flow through pipes is still in development

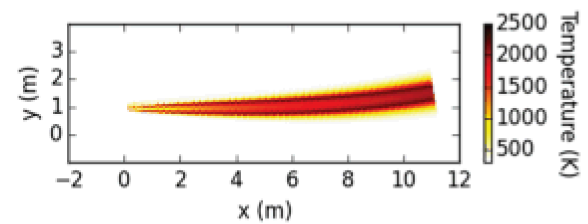


HYRAM
HYDROGEN RISK ASSESSMENT MODELS

Sandia National Laboratories

- Hydrogen Risk Assessment Model
  hyram.sandia.gov
- Generic data for gaseous hydrogen (GH2) systems:
  component leak frequencies, ignition probability; modifiable by users
- Models of GH2 physical effects for consequence modeling
  - Release characteristics (plumes, accumulation)
  - Flame properties (jet fires, deflagration within enclosures)
- Probabilistic models for human harm from thermal and overpressure hazards
- Fast running: to accommodate rapid iteration
- Calculates common risk metrics for user-defined systems: FAR, AIR, PLL; frequency of fires
- Ongoing development activities to add liquid hydrogen systems and features to add usability





Solicit Input for What's Next

- Different ventilation configurations
- HAZOP studies

- HyRAM for NG: hyram.sandia.gov
- Is NFPA 30A open to a risk based standard?

Extra Slides

Scenarios Modeled in Phase 1

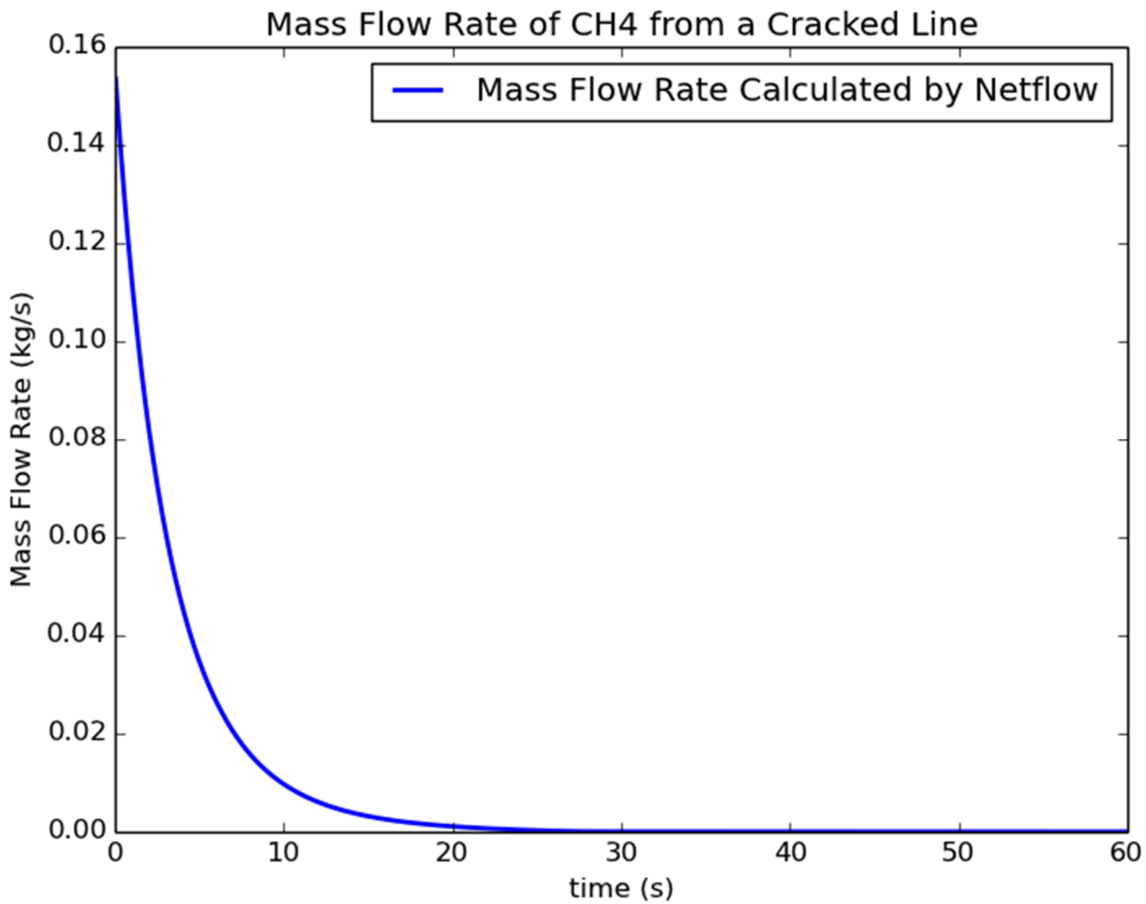
Scenarios Modeled in Phase 1							
	HAZOP Number	Component	Hazard Scenario	Causes	Consequences	Notes	Modeling Notes
	7	LNG-4 (LNG tank)	Overpressure of tank and proper operation of relief valve	Excessive hold time, insulation failure	Minor release of GNG	Fuel was vented from the top of the bus.	Modeled in Phase 1 As Modeling Scenario 1
	14	CNG-1 (Cylinders)	Overpressurization of Cylinder	External fire AND successful operation of PRD	Potential catastrophic release of CNG		Modeled in Phase 1 As Modeling Scenario 4 - although the active fire was not included in the model. The bug in the model from Phase 1 run has been fixed with little impact on the model result.
	19	CNG-3 (Pressure Relief Device)	PRD fails open below activation pressure	Mechanical defect, material defect, installation error, maintenance error	Potential catastrophic release of CNG		
	NA	LNG Bleed Valve	Residual pressure is vented from fuel system downstream of isolation valve.	Intentional	Small release of fuel in the lines.	Fuel was vented from the side of the bus.	Modeled in Phase 1, Scenario 2 (not actually in report, since Scenario 3 would be a worse case.)
	NA	CNG - 7 Bleed Valve	Residual pressure is vented from fuel system downstream of isolation valve.	Intentional	Small release of fuel in the lines.	Fuel was vented from the side of the bus.	Modeled in Phase 1, Scenario 3

New Scenarios to be Modeled

HAZOP Number	Component	Hazard Scenario	Causes	Consequences	Notes	Modeling Notes
5	LNG-3 (Heat exchanger)	External leakage from heat exchanger	Leaks of LNG or GNG due to defective materials, corrosion, thermal fatigue, pressure rupture, etc.	Catastrophic release of LNG or GNG	Because heat exchangers are comprised of small diameter tubes with many bends, they are suseptible to stress, corrosion, and cracking failures. For Heavy Duty vehicles especially, the vibration environment was considered to increase the frequency of these failures.	Potential multi-phase flow from leak point will require NetFlow to handle bi-phase flow. Can be simulated in smaller garage than Phase 1.
12	LNG-5 (Pressure relief valve)	Failure of PRV to reclose after proper venting, fails open	Mechanical Failure	Total volume of tank released	Because the pressure in the LNG is much lower than a CNG cylinder, the mass release rate should be lower. However, the total mass of natural gas release would be larger, just spread out over a longer period of time.	The effects of the lower, longer release on the combustible mass cloud extents could have an impact on the ventilation requirements and sensor placement.
15	CNG-1 (Cylinders)	Outlet or fitting on tank fails	Manufacturing defect or installation or maintenance error	Potential catastrophic release of CNG	For Light Duty vehicles, the release point and orientation should be modeled in a smaller facility. Release orifice size may also be smaller that the normal PRV diameter.	Need to identify typical or representative dimensions of a Light Duty vehicle service facility, such as an OEM service bay.
35B	CNG-20 (Tubing)	Leakage from tubing	Mechanical damage, material failure, installation error	Potential release of CNG		Impact on Light or Medium Duty vehicle facilities may need to be modeled, including release height and orientation. Possibly same or similar leak as in Scenario 3 above.
37	Multiple	Human error or disregard for maintenance procedures	Procedures violated (Gas train not emptied, tank not isolated)	Total volume of system released		This model parameters may be similar to to the original large-scale CNG release, however release orifice size, height and orientation may need to be modeled.

Scenario 3: CNG Fuel System Line Cracking

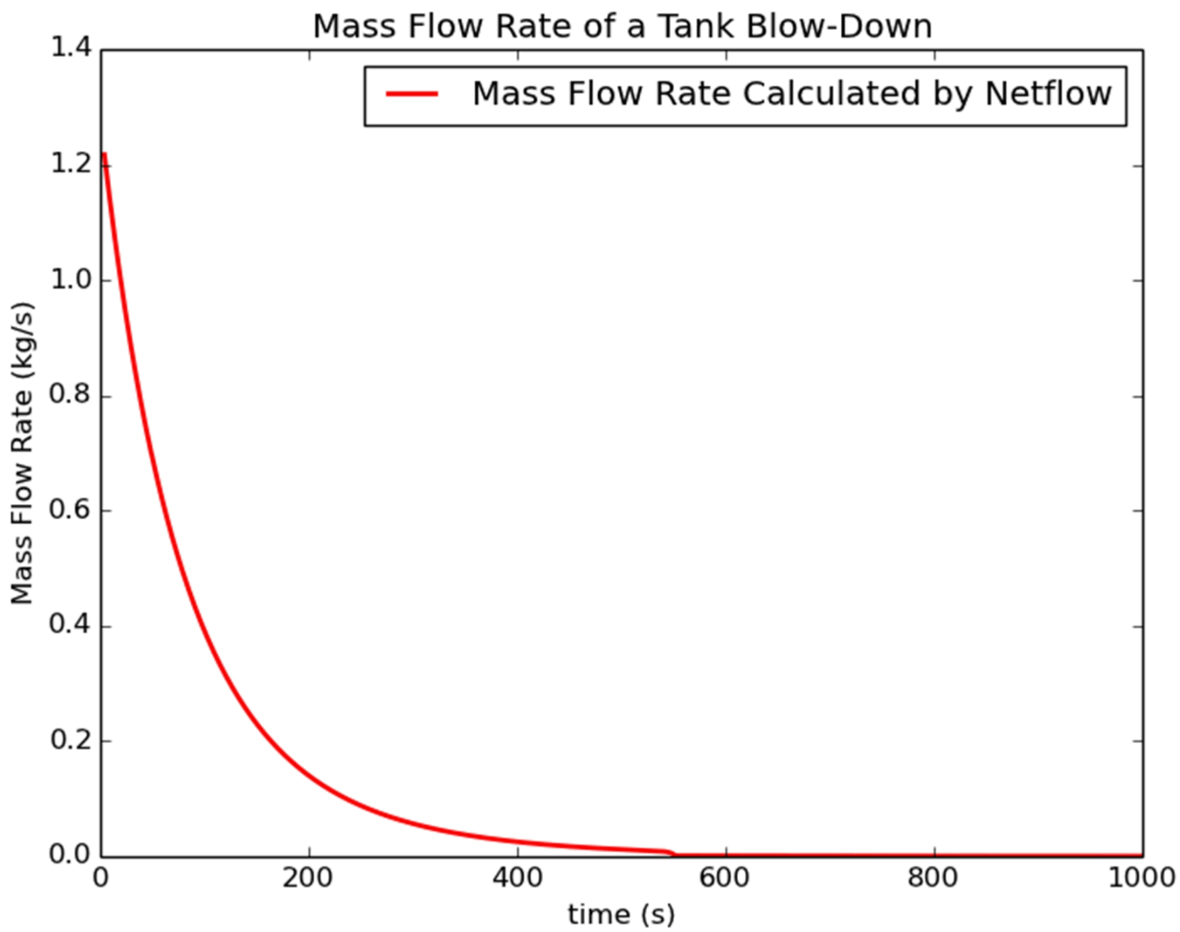
3.3 liters @ 248 bar; 3% area leak 1.27 cm ID tubing



Play movie: Sideleak.avi

Scenario 4: Mechanical Failure PRD Release

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



Play movie: CNG_Blowdown.avi

HAZOP Structure

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- 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