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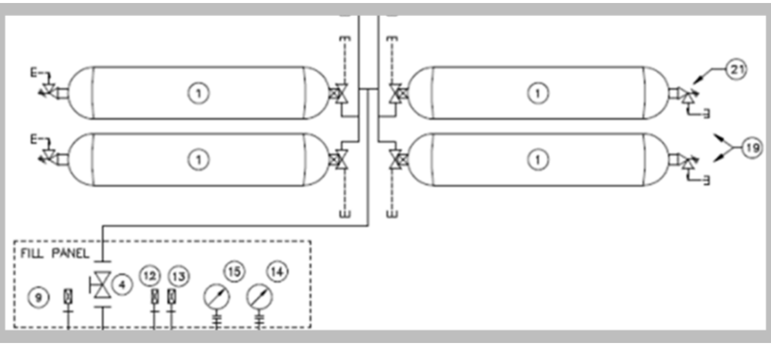
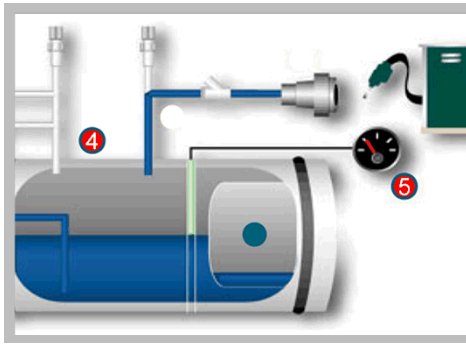
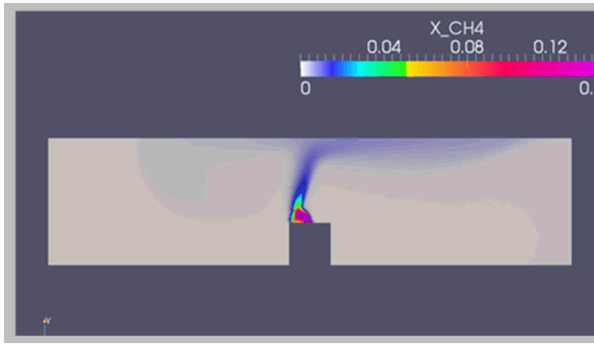






Risk-Informed LNG/CNG Maintenance Facility Codes and Standards

Project sponsored by DOE Clean Cities:

Technical & Analytical Assistance

Myra Blaylock, PhD

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

SAND NO. 2017-

Talk Objectives

- Review Sandia work
  - Hazardous and Operability Study (HAZOP)
  - Best Practices to mitigate hazards
- Get feedback from NGVTF on Best Practices and Scenarios
  - myra.blaylock@sandia.gov
- New website: altfuels.sandia.gov
  - Reports, videos, links, information, these slides

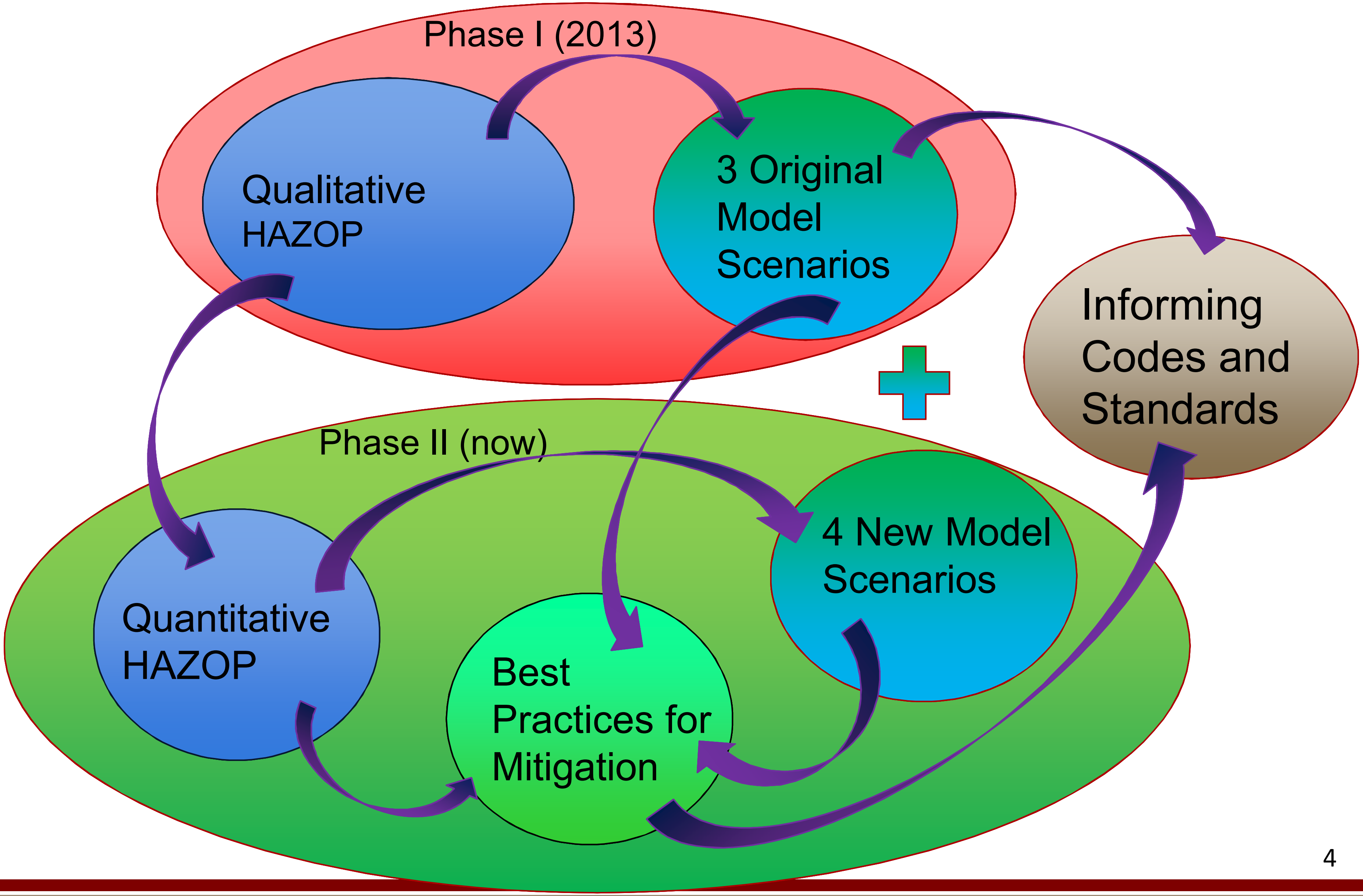
Project Motivation

- 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

Image: http://www.energyburrito.com/tag/natural-gas-vehicles/

Flow Chart



Phase I (2013)
Qualitative HAZOP
3 Original Model Scenarios
Informing Codes and Standards
Phase II (now)
Quantitative HAZOP
Best Practices for Mitigation
4 New Model Scenarios

HAZOP and Model Recommendations

HAZOP Frequency

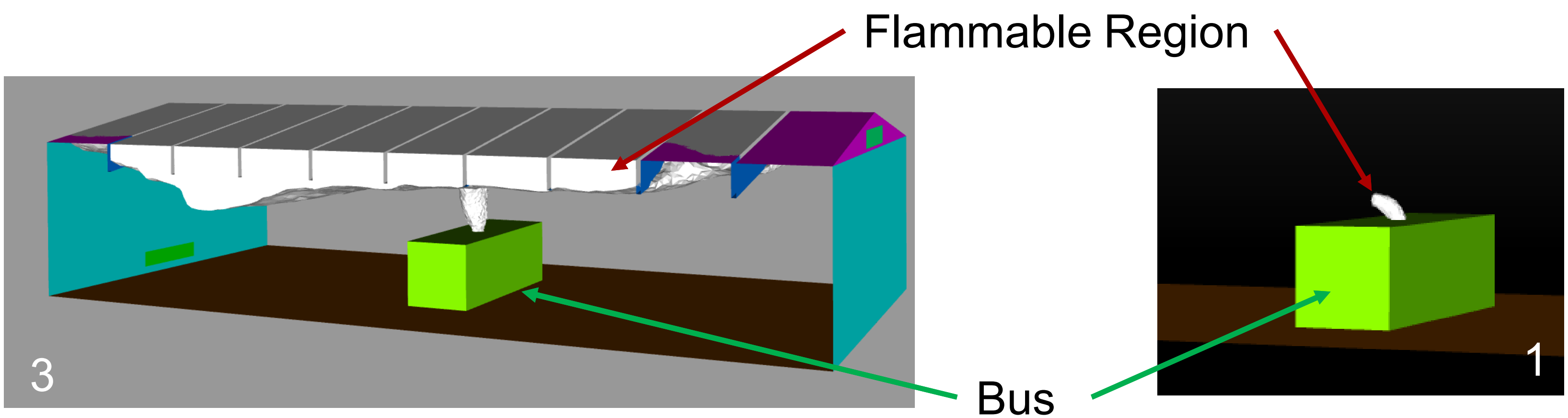
- Failure Definition – Unexpected or uncontrolled release of natural gas (liquid or gaseous phase)

Frequency Classifications for Release			
5	Intentional: Incident will occur on a set time frame		certain
4	Anticipated: Incidents that might occur several times during the lifetime of the facility	$f > 10^{-2}$/yr	1 in a 100 years
3	Unlikely: Events that are not anticipated to occur during the lifetime of the facility	10^{-4}/yr $< f \leq 10^{-2}$/yr	
2	Extremely unlikely: Events that will probably not occur during the occur during the lifetime of the facility	10^{-6}/yr $< f \leq 10^{-4}$/yr	
1	Beyond extremely unlikely: All other incidents	$f \leq 10^{-6}$/yr	1 in a million years

HAZOP Consequence

- Consequence: How big is the release?

Consequence Classifications for Release	
3	Major (all contents of tank) release of natural gas (for CNG multiple cylinders)
2	Moderate release of natural gas (for CNG one cylinder)
1	Minor release of natural gas



HAZOP Escalation Factor

- Escalation : Assuming a release, what are the chances it will escalate? (i.e. Catch on fire)

Escalation Factor for Release		
4	Certain	Ignition is already present (+ faster release)
3	High	Faster release
2	Medium	Slow, large release
1	Low	Employee present

HAZOP Examples

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Frequency	
5	Intentional
4	Anticipated
3	Unlikely
2	Extremely unlikely
1	Beyond extremely unlikely

Consequence	
3	Major
2	Moderate
1	Minor

Escalation Factor	
4-Certain	Ignition is already present (+ faster release)
3-High	Faster release
2-Medium	Slow, large release
1-Low	Employee present

Hazard Scenario	Causes	Description	Consequence	Frequency	Escalation	Rank
LNG: Overpressure of tank due to warming and proper operation of relief valve	Excessive hold time, insulation failure	Minor release of GNG	1	5	Low	5
CNG: Outlet or fitting on tank fails	Manufacturing defect, instillation or maintenance error	Potential catastrophic release of CNG	2	3	High	18

HAZOP Scenarios Selected for Further Analysis

HAZOP Scenario Number		Consequence	Frequency	Escalation Factor
1	External leakage from LNG regulator body	1	4	L
7	Overpressure of LNG tank and proper operation of relief valve	1	5	L
12	Failure of LNG PRV to reclose after proper venting	3	4	H
14	Overpressure of cylinder due to external fire	3	2	H
15	Outlet or fitting on CNG cylinder fails	2	3	H
19	CNG PRD fails open below activation pressure	2	4	H
35B	Leakage from CNG tubing	3	4	L
37	Human error or disregard for maintenance procedures	3	3	H

HAZOP Scenarios Selected for Further Analysis

HAZOP Scenario Number		Heavy-Duty Vehicle Representative Facility Modeling Number (100' x 50' x 20')		Light-Duty Vehicle Representative Facility Modeling Number (60' x 40' x 20')	
1	External leakage from LNG regulator body	A/B	LNG blow-off	N/A	
7	Overpressure of LNG tank and proper operation of relief valve	A	LNG "Burping"/ "Weeping"	N/A	
12	Failure of LNG PRV to reclose after proper venting	G	(Modeling capabilities in development)	N/A	
14	Overpressure of cylinder due to external fire	F	Analytical Jet Fire (In development)	F	Analytical Jet Fire (In development)
15	Outlet or fitting on CNG cylinder fails	C	PRD failure for a CNG cylinder	E	PRD failure for a CNG cylinder
19	CNG PRD fails open below activation pressure	C	PRD failure for a CNG cylinder	E	PRD failure for a CNG cylinder
35B	Leakage from CNG tubing	B	CNG fuel system line cracking	D	CNG fuel system line cracking
37	Human error or disregard for maintenance procedures	All	Covered by other scenarios	All	Covered by other scenarios

Best Practices to Mitigate Hazards

Example - LNG "Burping" Release

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

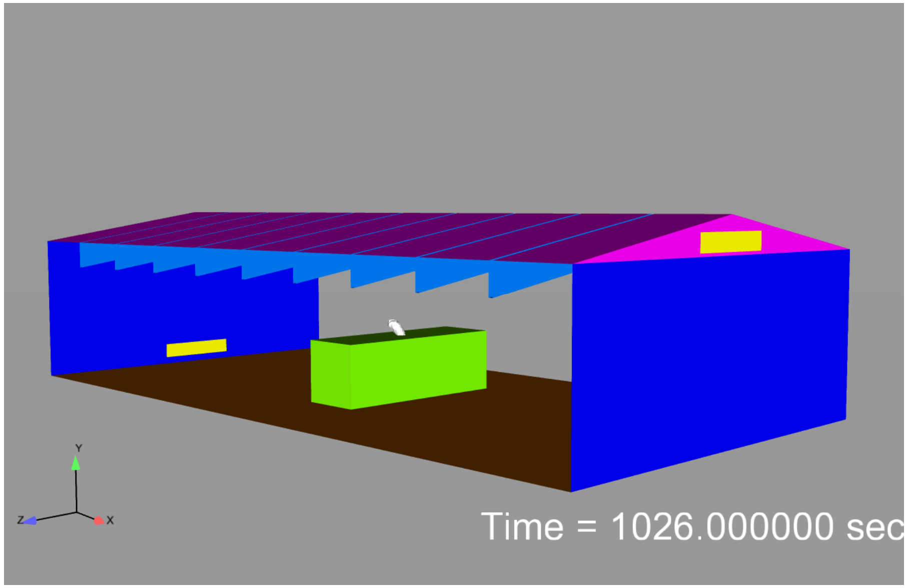
Best practices were reviewed across the event sequence of the LNG burp

Release Prevention Features	
Design	Administrative
	2 -Preventative Maintenance – purposefully reducing pressure outside 6 -Operator Training - hold times

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

Best Practices Example: LNG "Burping"

- Modeling results show no flammable concentration at the ceiling.
- Best practices can target specific consequences more strategically.
- They can also be applicable for facilities smaller or of a different layout than the maintenance garage modeled.



Best Practices Example: LNG "Burping"

- Administrative Procedure: **Operate the vehicle engine periodically so that the hold time is not exceeded.**
  - This will maintain the LNG tank pressure below its seat pressure of 180 psig.
  - An administrative control to operate the vehicle(s) on a regular basis would reduce the frequency of release due to pressure buildup.
  - This best practice would prevent the release

Image: http://www.quora.com

Best Practices Example: LNG "Burping"

- Administrative Procedure: **Check the vehicle's pressure gauge on a regular basis for pressure buildup.**
  - The pressure gauge for the tank shows when the tank is close to an overpressure buildup (and subsequent release through the PRV).
  - An administrative control to check the vehicle's pressure gauge on a regular basis would allow the operator to determine the best time to operate the vehicle engine.
  - This practice would prevent the release.

Image: http://www.pumptec.com

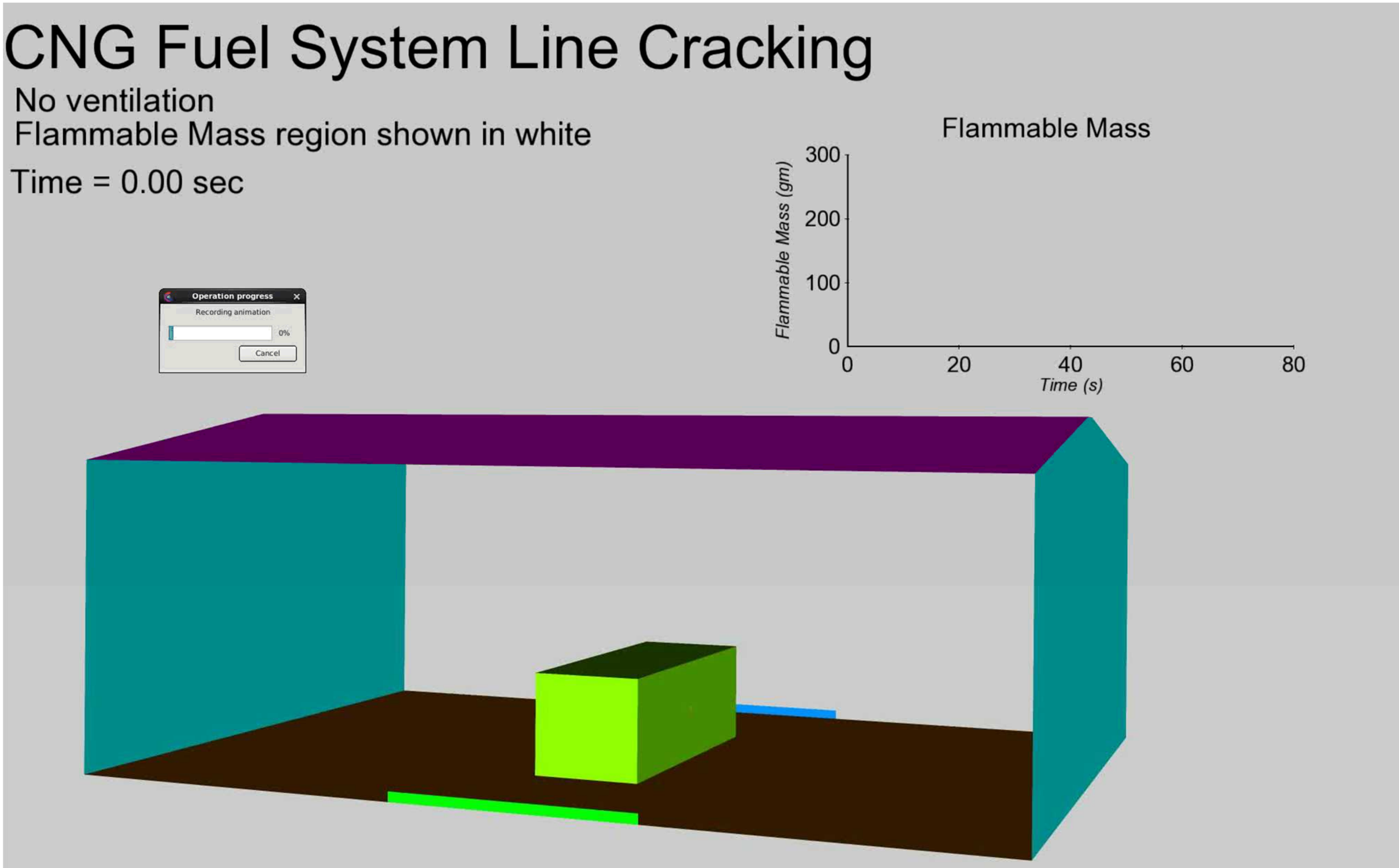
Best Practices Example: LNG "Burping"

- Design: **Install a flexible vent hose to connect the PRV to the facility's exhaust system.**
  - If an LNG burp occurs, the LNG vapor would exhaust to the outside of the facility.
  - This would prevent any flammable buildup inside the maintenance facility.
  - This practice would prevent the ignition of the release. It would not prevent the release itself.

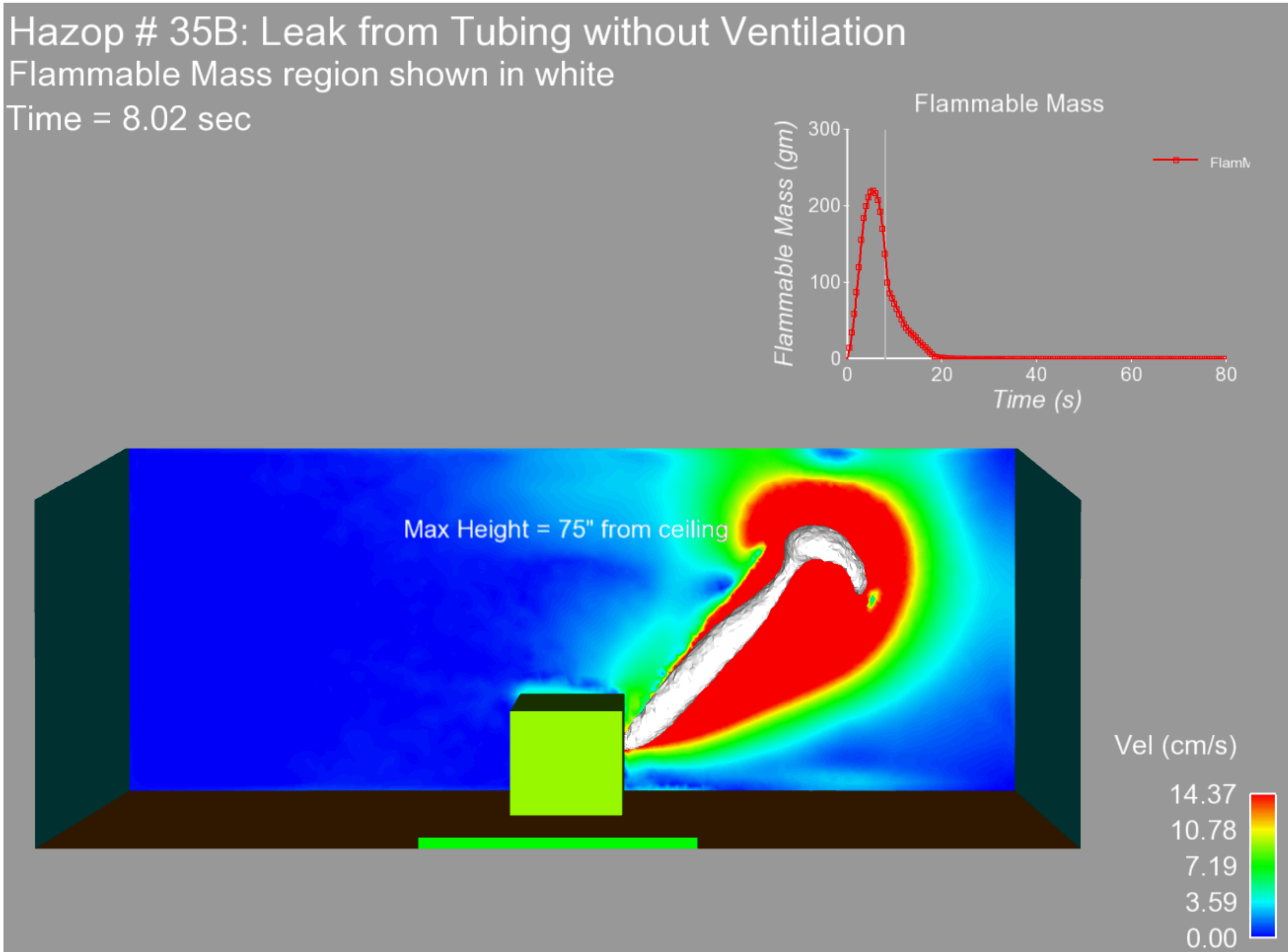
Image: http://www.auto-repair-manuals.com

Other Modeling Work

#35B: Small Garage

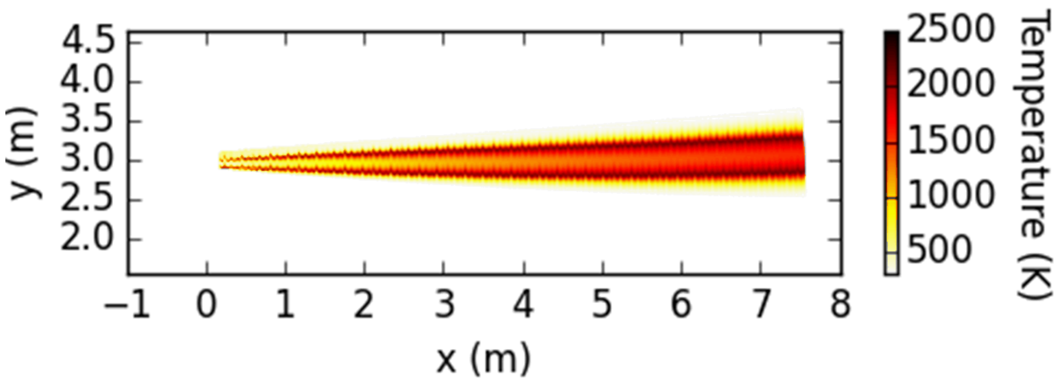


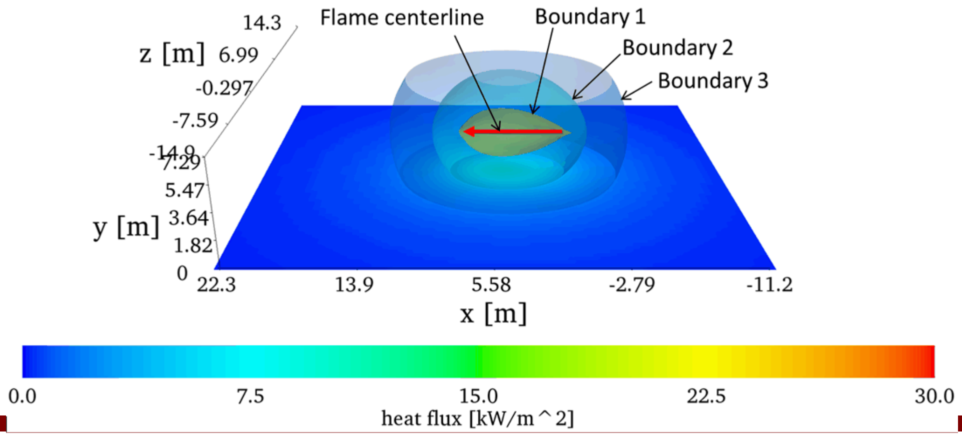
#35B: Small Garage



#14: Overpressure due to external fire

- 1D models
- Calculate jet plume length and heat flux





HAZOP Scenarios

HAZOP Scenario Number		Consequence	Frequency	Escalation Factor	Rank
1	External leakage from LNG regulator body	1	4	L	4
7	Overpressure of tank and proper operation of relief valve	1	5	L	5
12	Failure of LNG PRV to reclose after proper venting	3			
14	Overpressure of cylinder due to external fire	3			
15	Outlet or fitting on CNG cylinder fails	2			
19	CNG PRD fails open below activation pressure	2			
35 B	Leakage from CNG tubing	3	4	L	12
37	Human error or disregard for maintenance procedures	3	3	H	27

What have you experienced?

What keeps you up at night?

What’s Next?

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

  - Experiments to validate models (LNG)
  - Cold LNG leak simulations
  - Ignited leak size and heat flux

  - Suggestions?

Thank you!

altfuels.sandia.gov

Myra.Blaylock@sandia.gov

Extra Slides

HAZOP Scenarios

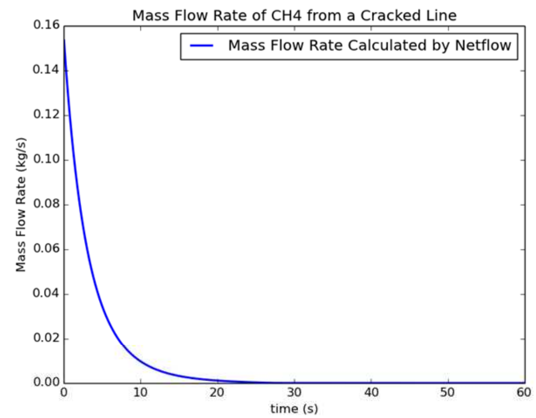
HAZOP Scenario Number		Consequence	Frequency	Escalation Factor	Rank
1	External leakage from LNG regulator body	1	4	L	4
7	Overpressure of tank and proper operation of relief valve	1	5	L	5
12	Failure of LNG PRV to reclose after proper venting	3	4	H	36
14	Overpressure of cylinder due to external fire	3	2	H	18
15	Outlet or fitting on CNG cylinder fails	2	3	H	18
19	CNG PRD fails open below activation pressure	2	4	H	24
35 B	Leakage from CNG tubing	3	4	L	12
37	Human error or disregard for maintenance procedures	3	3	H	27

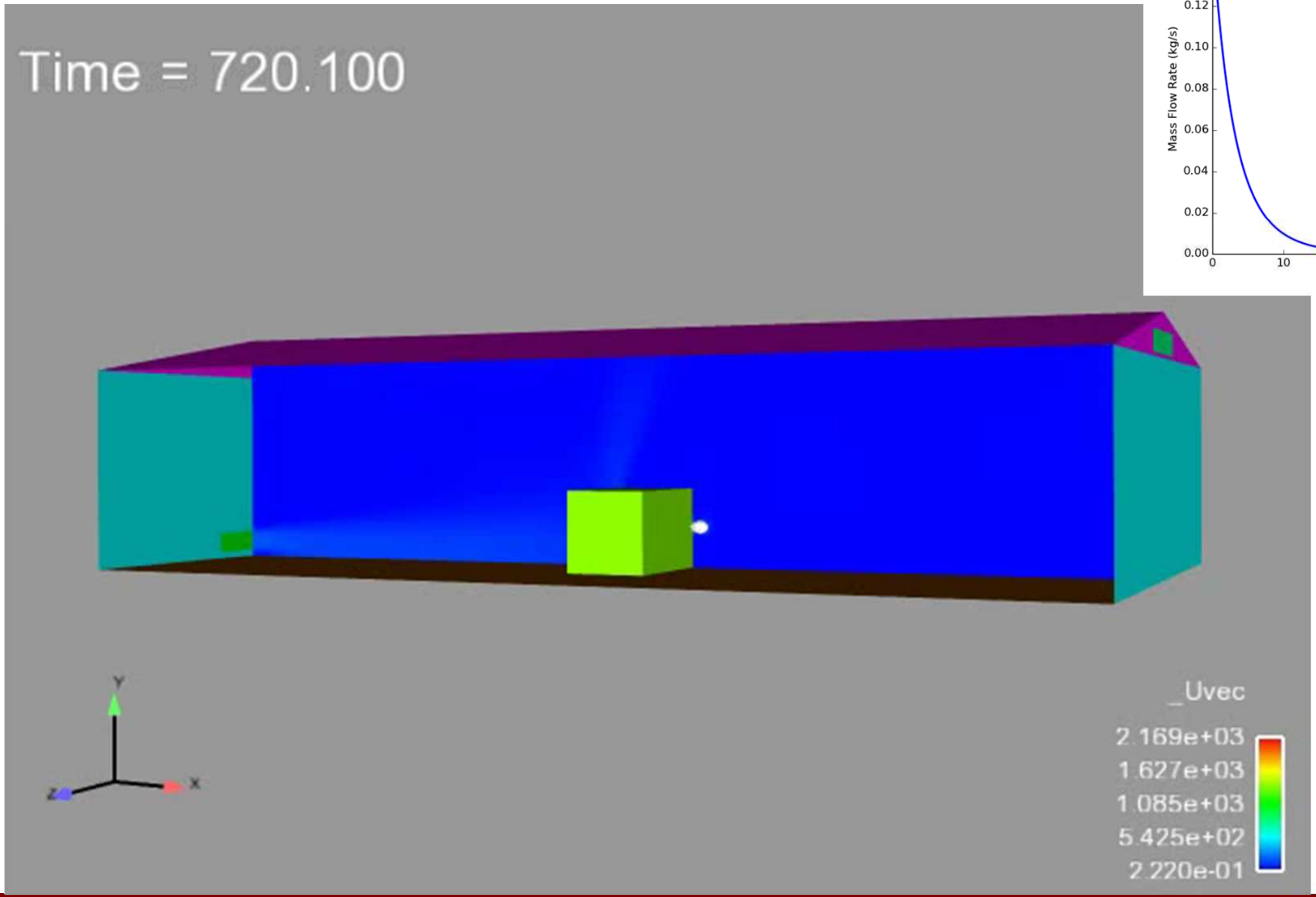
Next 8

HAZOP Scenario			Conse-quence	Frequency	Escalation Factor	Rank
5	LNG-3 (Heat exchanger)	External leakage from heat exchanger due to defective materials, corrosion, etc.	2	3	M	12
4B	LNG-2 (Fuel Shutoff Valve	Valve fails to shut completely, or leaks external or in-process	3	2	M	12
6A	LNG-4 (LNG tank)	Overpressure of tank and failure of relief valve to open during a fire	3	1	C	12
8	LNG-4 (LNG tank)	Outlet or fitting on tank fails due to defect or installation error	3	2	M	12
	LNG-7 (Fill Port)	Release of GNG through fill port due to failure to check valve	3	2	M	12
13	CNG-1 (Cylinders)	Overpressurization of Cylinder due to External fire AND failure of PRD to operate	3	1	C	12
18	CNG-2 (Cylinder Solenoid Valve)	External leakage of CNG through body of solenoid or joint due to Mechanical damage, material failure, installation error	2	3	M	12
20	CNG-3 (Pressure Relief Device)	External leakage through PRD of CNG due to Mechanical defect, material defect, installation error, maintenance error	2	3	M	12

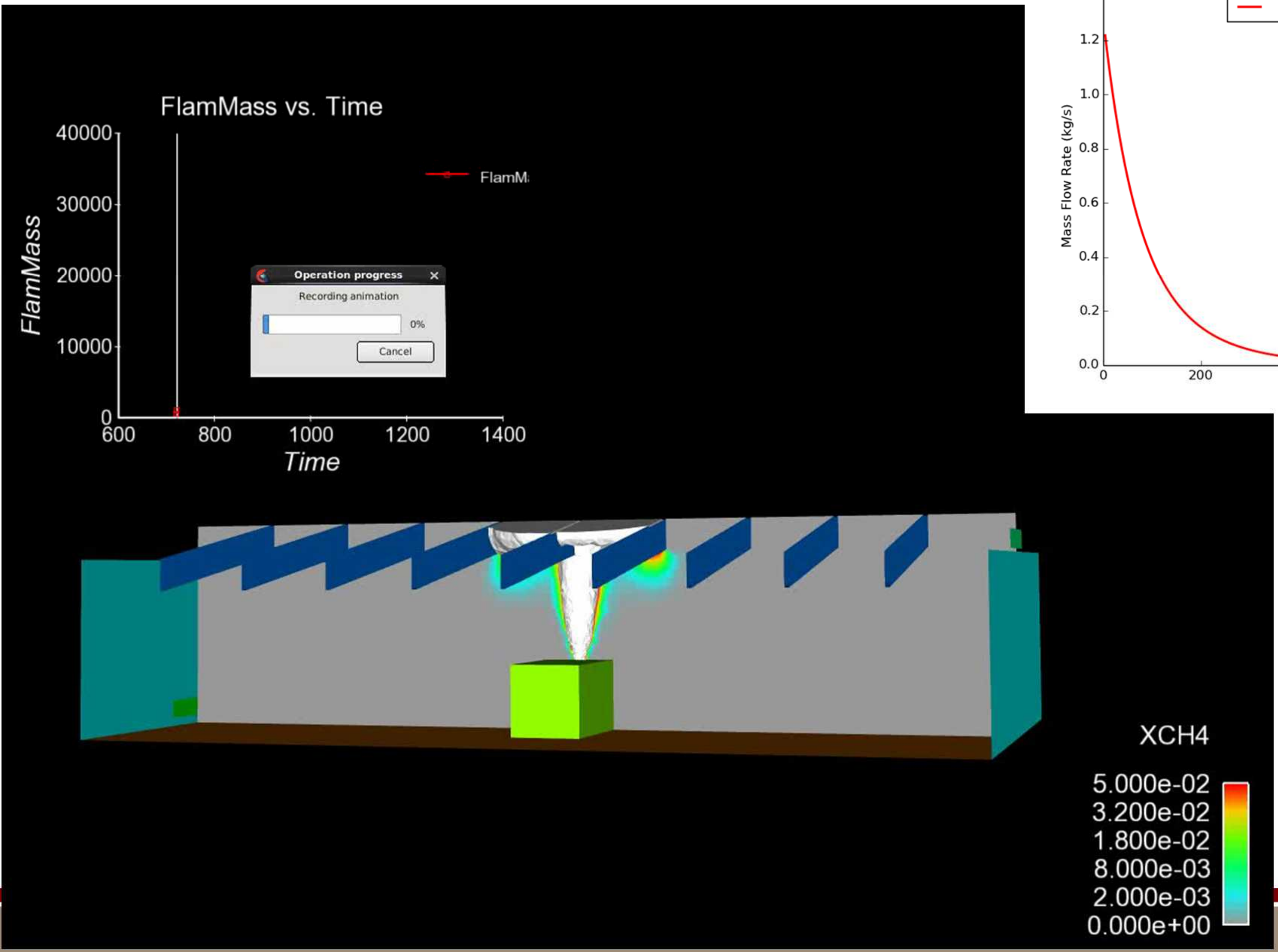
Scenario 3: CNG Vehicle Fuel System Line Cracking: 3.3 liters @ 248 bar; 3% area leak

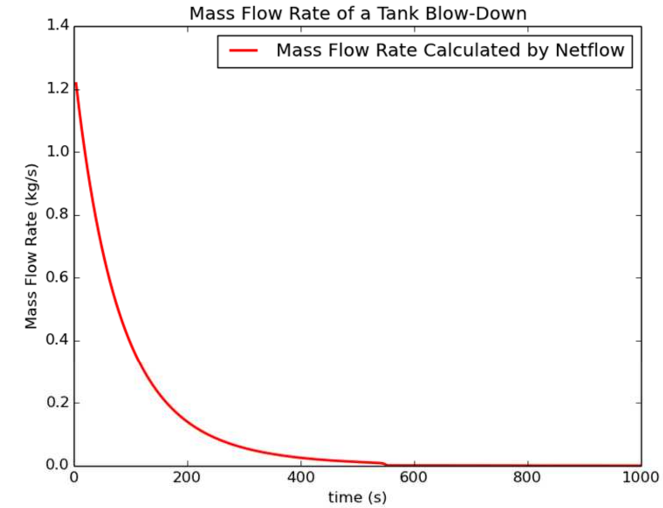
1.27 cm ID tubing





Scenario 4: Mechanical Failure PRD Release - 0.7 m^3 volume @ 250 bar from a 6.2 mm TPRD



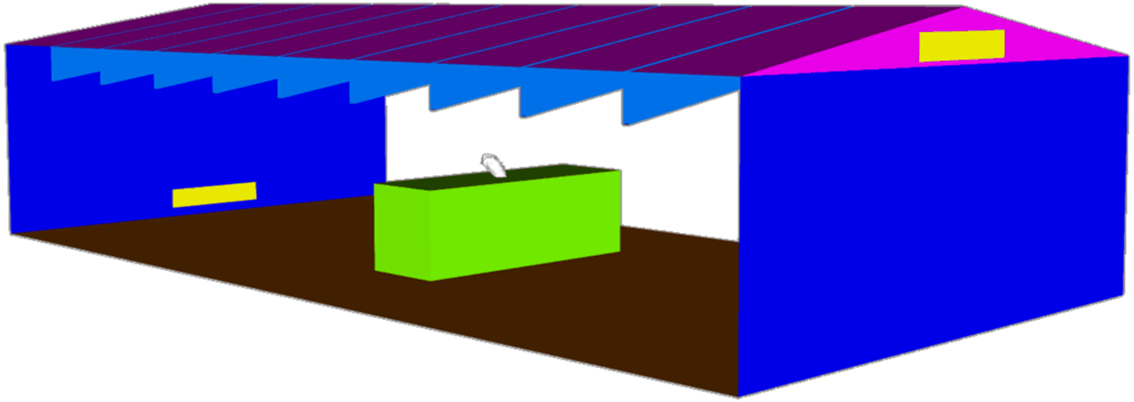


$$\Delta p_{max\ expansion} = 220\ kPa$$

Report at altfuels.sandia.gov

Natural Gas Vehicle Maintenance Garage

- Dimensions: 100’ x 50’ m x 20’ ; 1:6 roof pitch (60 x 40 x 20)
- 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’)



HYRAM
HYDROGEN RISK ASSESSMENT MODELS

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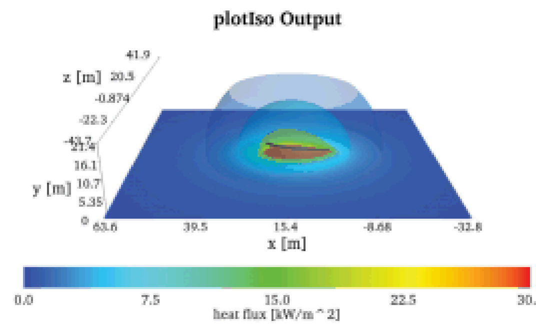
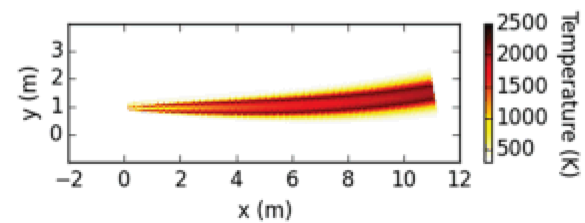
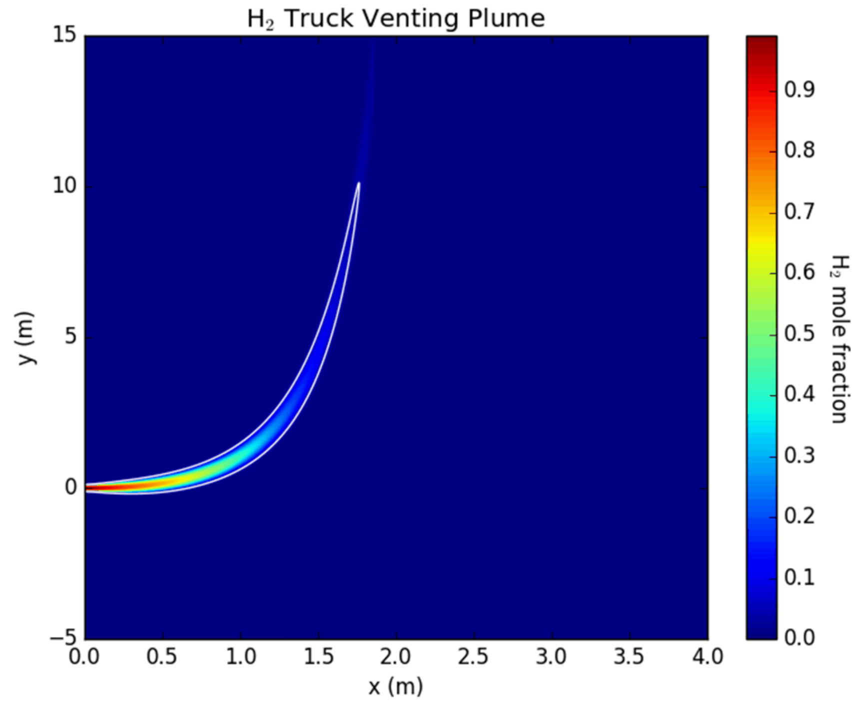
- Hydrogen Risk Assessment Model
  hyram.sandia.gov
- Generic data for gaseous hydrogen (GH2) systems:
  component leak frequencies, ignition probability; modifiable by users
- Models of GH2 physical effects for consequence modeling
  - Release characteristics (plumes, accumulation)
  - Flame properties (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





“Cold Plume” Capabilities For LNG

- Modeling leaks from a two-phase container is possible
  - From the top: gaseous region
  - From the bottom: liquid region
- Can use this to get rough calculations of plume characteristics
- Two phase flow through pipes is still in development



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
Replace fuel system components (e.g., 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 °F
No odorant in LNG
Interlocks that activate on gas detection
Use of power tools, lights, radios, cutting & welding (ignition sources)

Operational States

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

HAZOP Modeling Scenarios

Modeling Scenario	Scenario Description	Garage Details	Tank/Leak Volume	Tank Pressure	Leak Size	HAZOP Scenarios
A	LNG Blow-Off	Heavy Duty: 100'x50'x20' with a 1:6 pitched roof	1.7% of 700 liters = 2.3 kg	248 bar	Diameter = 6.2mm	1,7
B	CNG Fuel System Line Cracking	Heavy Duty: 100'x50'x20' with a 1:6 pitched roof	3.3 liters	248 bar	3.8 mm^2 3% of tubing size	35B
C	PRD Failure for a CNG Cylinder	Heavy Duty: 100'x50'x20' with a 1:6 pitched roof	700 liters	248 bar	Diameter = 6.2mm	15,19
D	CNG Fuel System Line Cracking	Light Duty: 60'x40'x20'with a pitched roof	3.3 liters	248 bar	3.8 mm^2 3% of tubing size	35B
E	PRD Failure for a CNG Cylinder	Light Duty: 60'x40'x20'with a pitched roof	700 liters	248 bar	Diameter = 6.2mm	15,19
F	Overpressure of CNG cylinder due to external fire	No Garage: 1D analysis only	700 liters	248 bar	Diameter = 6.2mm	14

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.