Risk Analysis and Modeling to Improve Hydrogen Fuel Cell Vehicle Repair Garages

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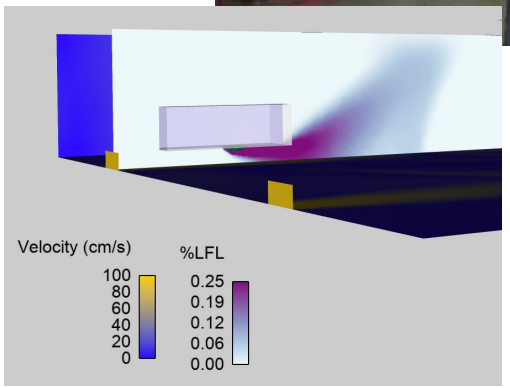

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Overview

Timeline

- Project start date: May 2018
- Project end date: October 2019

Barriers

A. Safety Data and Information: Limited Access and Availability
F. Enabling National and International Markets Requires Consistent RCS
G. Insufficient Technical Data to Revise Standards
L. Usage and Access Restrictions

Budget

- Total Project Value: $126k
  - DOE Funding: $60k
  - QAI Funding: $60k
  - QAI In-Kind Contributions: $6k

Partners

Quong and Associates, Inc.

Any proposed future work is subject to change based on funding levels

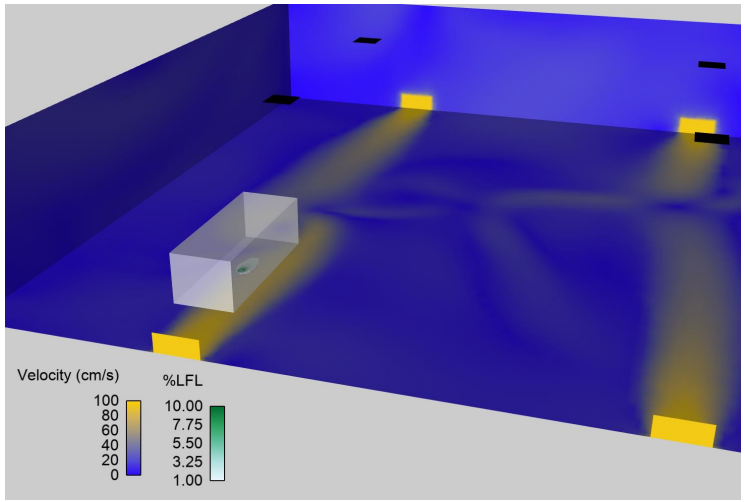
Relevance: H_2 Vehicle Repair Garage Infrastructure

Objective: Perform **application-specific risk analyses** to identify credible hazard scenarios resulting in unintentional **indoor releases** of hydrogen during **vehicle maintenance** operations, characterize key hydrogen release scenarios through **detailed modeling**, and improve code requirements.

SCS MYRDD Barrier	SNL Goal
A. Safety Data and Information: Limited Access and Availability	Publish publicly-available report based on risk and modeling analyses
F. Enabling National and International Markets Requires Consistent RCS	Perform risk analyses and modeling which enable science-based code decisions
G. Insufficient Technical Data to Revise Standards	Perform detailed modeling for repair garage indoor releases to support code improvement
L. Usage and Access Restrictions	Focus risk and modeling analyses on risk scenarios specific to repair garages

Approach: Risk Analysis and Modeling to Inform Code Requirements

- Risk Analysis
  - Repair garage application-specific risk assessment and credible scenario identification
- Modeling
  - Computational fluid dynamics (CFD) modeling for indoor hydrogen releases
  - Based on identified scenarios from risk assessment
- Code Recommendations
  - Results of risk analyses and modeling will be incorporated into proposals to improve requirements for repair garages while maintaining same level of safety



Risk Analysis for Identification of Leak Scenario

- Hazard and Operability Study (HAZOP)
  - Input from QAI and industry for H_2 FCV scenarios
  - Combination of maintenance activity, part, and failure type
- 490 unique possible combinations
  - 109 could lead to release of hydrogen
  - 23 releases that could occur in multiple maintenance activities
- High-risk scenarios ranked by:

Frequency	Description
5	**Intentional**: Incident will occur on a set time frame
4	**Anticipated**: Incident might occur several times during the lifetime of the facility
3	**Unlikely**: Events that are not anticipated to occur during the lifetime of the facility
2	**Extremely unlikely**: Events that will probably not occur during the lifetime of the facility
1	**Beyond extremely unlikely**: All other incidents

Severity	Description
3	**Major**: Release of full inventory of hydrogen
2	**Moderate**: Release of 1 tank of hydrogen (half of full inventory)
1	**Minor**: Small release of hydrogen

Risk Matrix Results for Scenarios of Interest

	Event Description	Release Scenario	Comments
A	External fire causes TPRD release of H_2 cylinders	2 tanks, high pressure, jet fire (worst consequence)	Only occurs when external fire heats H_2 storage; ventilation does not protect against this
B	Small release in low-pressure system	<1 tank, low pressure (most likely)	Mitigated by detection; the event below bounds this scenario
C	Premature disconnect of venting tool	1 or 2 tanks, low pressure	Focus of modeling due to relatively high risk score and possibility for operator error
D	Premature disconnect of high pressure defueling tool	1 tank, high pressure	Low probability of occurring

	Consequence		
Frequency	1	2	3
1	1	2	3
2	2	4	6 (A)
3	3	6 (D)	9
4	4	8 (C)	12
5	5 (B)	10	15

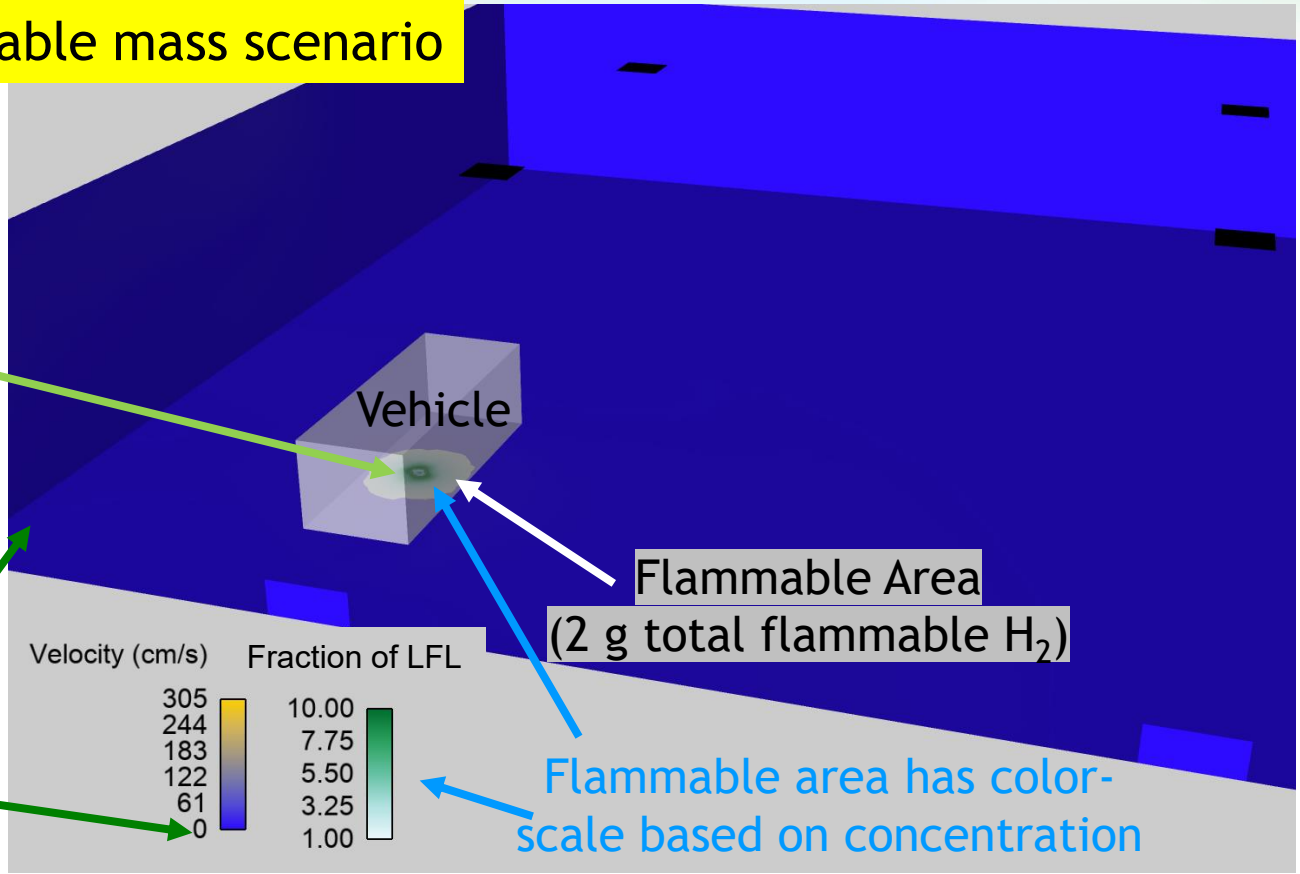
Modeling Scenarios Analyzed

- **Event: vent hose severed while vehicle defueling to an external exhaust outlet**
  - No ventilation
  - Regular ventilation (1 cfm/ft^2) near the vehicle
  - Regular ventilation (1 cfm/ft^2) away from the vehicle
  - Higher ventilation (300 cm/s) near the vehicle
- Typical 12-bay garage
  - Each bay 14’ x 27’ x 16’
  - Center aisle 6’ x 84’ x 16’
- Leak:
  - 2.5 kg of H_2 released
    - Most hydrogen vehicles have 2 tanks which store approximately 2.5 kg of hydrogen each
    - Energy equivalent to 2.5 gallons of gasoline
  - Release from mid-pressure port: 1.5 MPa (217.6 psi)
- Computer modeling simulates the leak and shows:
  - Direction of ventilation and released gas
  - Any areas of flammable mixture (Lower Flammability Limit (LFL) = 4 mol%)
- Total flammable mass is critical safety metrics considered

Low Pressure Release, No Ventilation

Maximum flammable mass scenario

Leak comes from center of bottom of vehicle

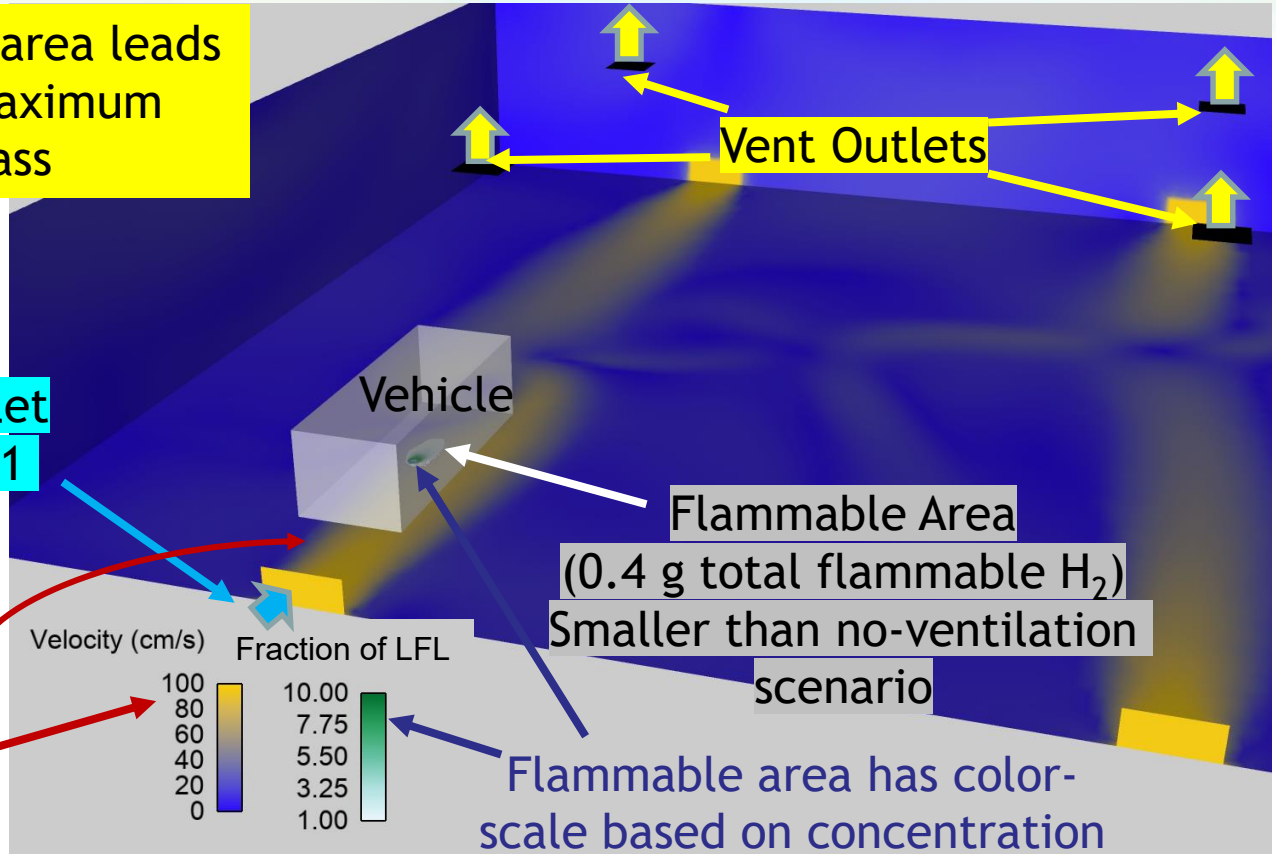


Blue walls and floor mean 0 cm/s velocity Showing no air movement for no-ventilation scenario

Flammable area has color-scale based on concentration

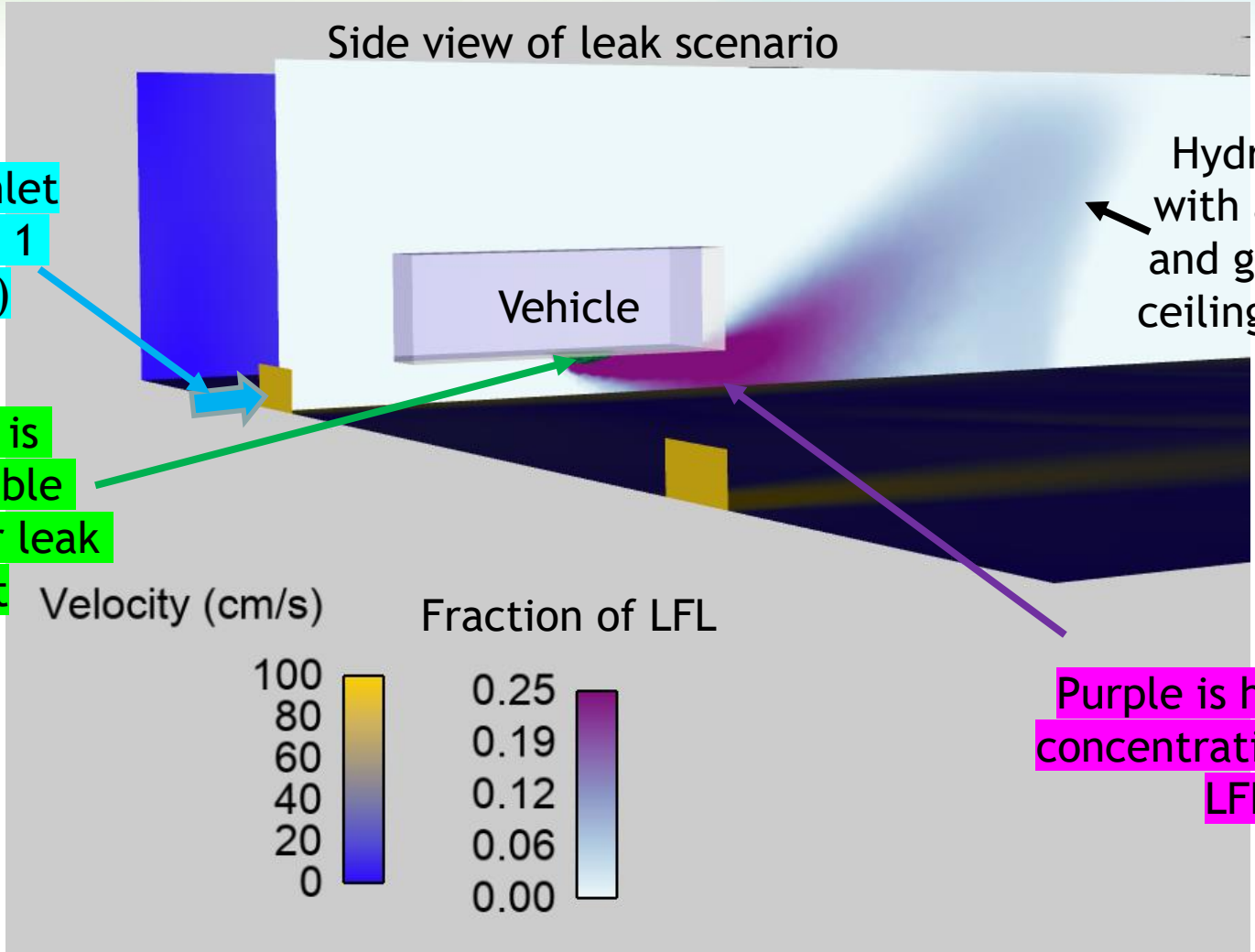
Low Pressure Release, Ventilation Near Leak

Ventilation near leak area leads to a decrease in maximum flammable mass



Yellow on walls and floor mean ~100 cm/s velocity Showing air movement from ventilation

Same Scenario: Showing Dissipation



Vent Air Inlet (4 inlets, 1 cfm/ft^2)

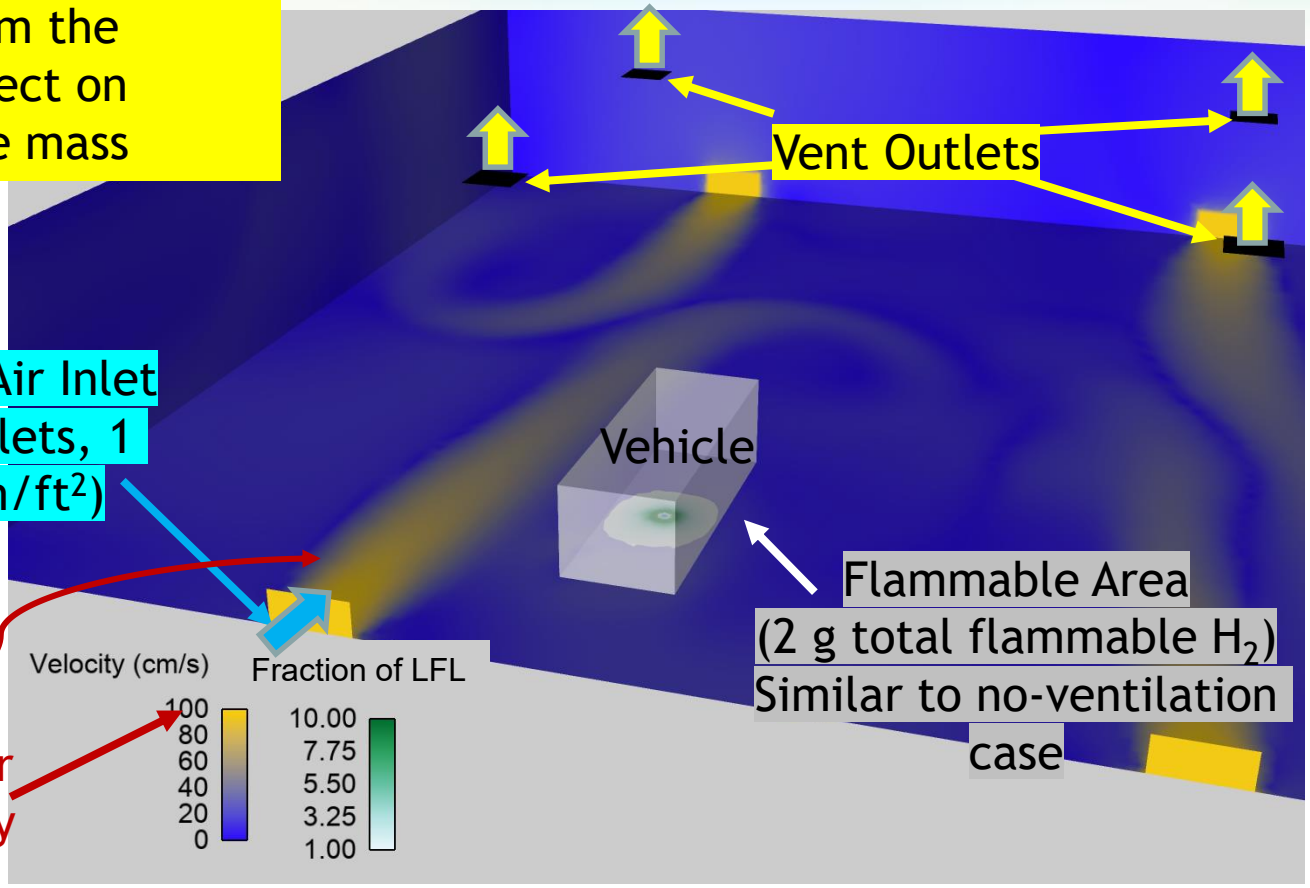
Green is flammable area near leak point

Hydrogen mixes with air (diluting) and going towards ceiling vent outlets

Purple is hydrogen concentration below LFL

Low Pressure Release, Ventilation Away From Vehicle

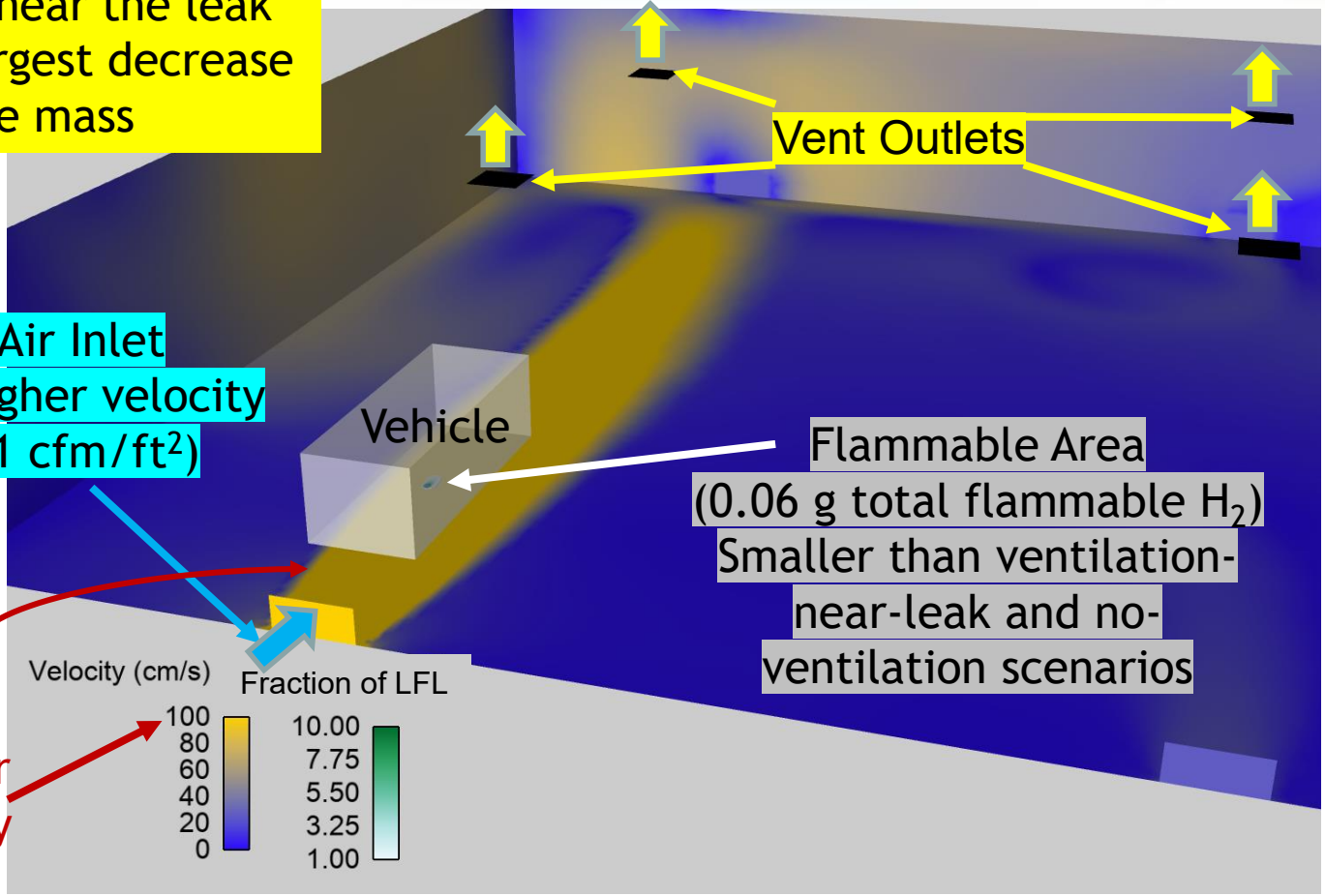
Ventilation away from the vehicle has little affect on maximum flammable mass



Yellow on walls and floor mean ~100 cm/s velocity Showing air movement from ventilation

Low Pressure Release, Higher Ventilation Near Leak

Higher ventilation near the leak area leads to the largest decrease of flammable mass



Yellow on walls and floor mean >100 cm/s velocity Showing air movement from ventilation

Hazard Quantification Summary for Low Pressure

- Flammable mass
  - Total flammable mass of hydrogen in garage based on wherever the local hydrogen concentration is >LFL
  - Cut-off: >4 mol% H_2 (LFL)
- No-ventilation case has low amount of flammable mass relative to mass released (<0.1% of 2.5 kg)
  - Due to dispersion of hydrogen in large area
  - Also due to slow (low pressure) release
- Ventilation near leak area leads to 80% to 97% decrease in maximum flammable mass
- Ventilation away from leak has little effect on maximum flammable mass

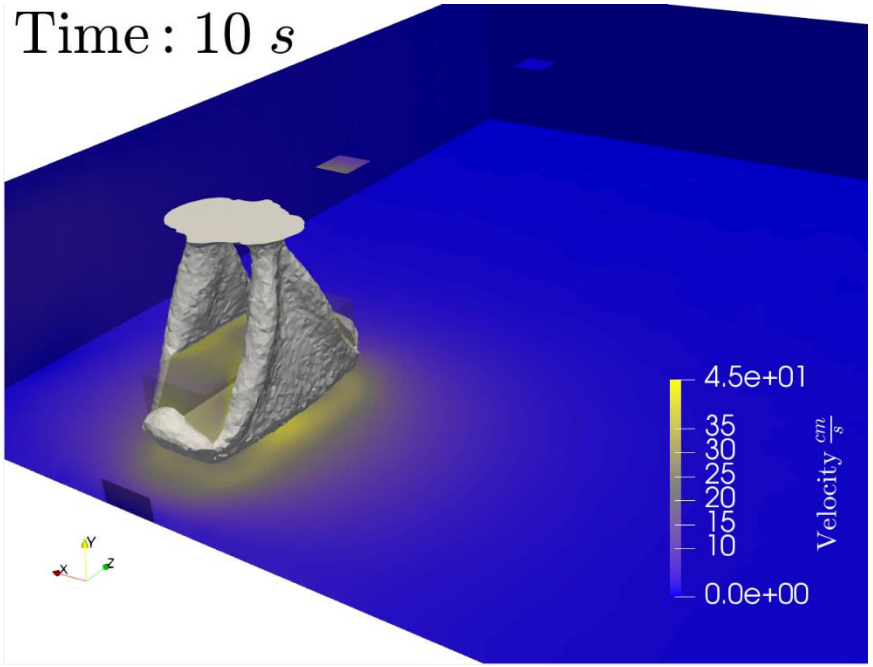
Scenario	Maximum Flammable Mass (g)
No Ventilation	2
Standard ventilation near leak	0.4
Standard ventilation away from leak	2
Higher velocity ventilation near leak	0.06

1,000 g of hydrogen ≈ 1 gallon of gasoline

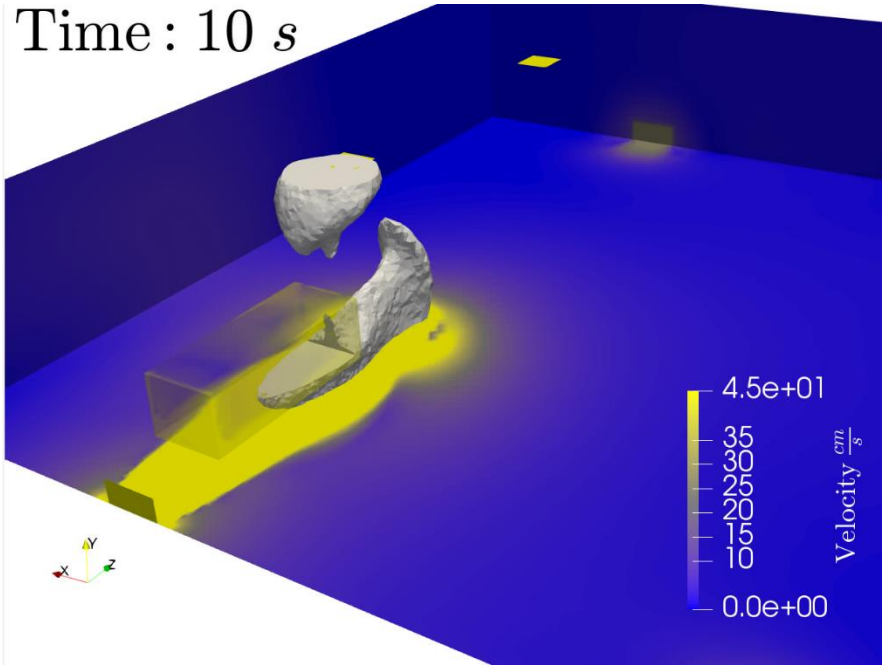
High Pressure Releases

Same scenarios as before, but with 70 MPa release instead of 1.5 MPa

No Ventilation



Higher Velocity Ventilation Near Leak



Hazard Quantification Summary for High Pressure

- No-ventilation case has low amount of flammable mass relative to mass released
  - ~4% of 2.5 kg
- High-velocity ventilation near leak area leads to **34%** decrease in maximum flammable mass
- High leak rate means that hazardous condition only lasts for short time
  - ~3 minutes for ventilation cases

Leak Pressure	Ventilation	Max Flammable Mass (g)
High	**None**	**94**
High	**Normal, Near**	**100**
High	**High, Near**	**62**
Low	None	2.0
Low	Normal, Away	2.2
Low	Normal, Near	0.4
Low	High, Near	0.05

Remaining Challenges & Barriers

- Risk analysis and modeling performed for large repair garage
  - Other structures (parking, small garages) could have different hazards and geometries
  - **Both garage and ventilation can vary widely**
  - Setting up and performing simulations for all sorts of different geometries is time- and computationally-expensive
- Incorporation of results into safety codes and standards
  - Results and recommendations need to be translated into improved code requirements that maintain same level of safety

Summary

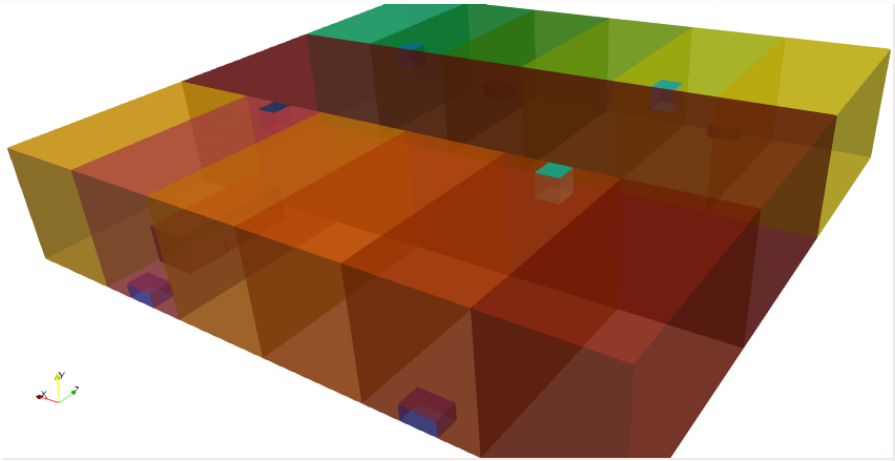
- **Relevance:**
  - Providing risk- and technical-basis for improvements to hydrogen repair garage safety codes and standards requirements
- **Approach:**
  - Risk analysis to identify critical scenarios of concern
  - Detailed modeling to characterize scenarios
  - Inform safety codes and standards improvements
- **Accomplishments**:
  - Defined key scenarios from risk analysis
    - Defueling vehicle inside garage
  - Modeled key scenarios
    - Flammable mass small relative to total mass released
    - Hazard location is not always evenly on ceiling
    - Ventilation near leak is most effective at reducing flammable mass
  - Prepared codes and standards proposals (QAI)

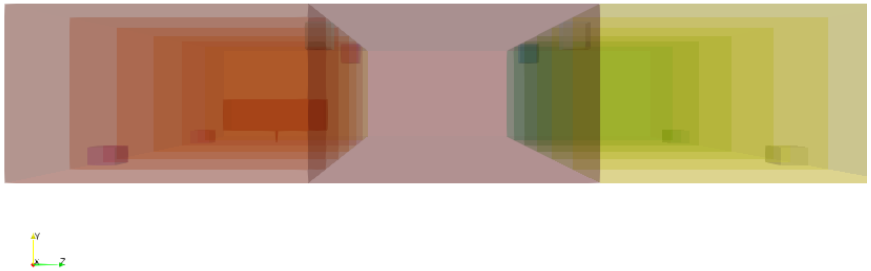
TECHNICAL BACKUP SLIDES

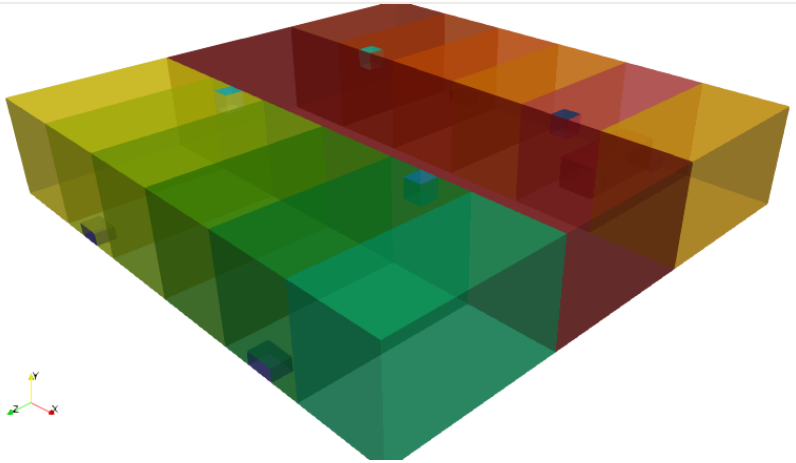
HAZOP Scenarios

Process Part	Operation States	Event Description	Consequence	Frequency	Risk Metric
Tank manual valve	1,2,3,4,5,6,7	Spontaneous Leak	1	2	2
Tank manual valve	1,2,5,6,7	Damage causes leak	1	3	3
Tank PRD	1,2,3,4,5,6,7	Spontaneous Leak	1	2	2
Tank PRD	1,2,3,4,5,6,7	Fire	3	2	6
Tank PRD	1,2,5,6,7	Damage causes leak	1	3	3
Defueling valve	1,2,3,4,5,6,7	Spontaneous Leak	1	2	2
Defueling valve	1,2,5,6,7	Accidental operation	2	2	4
Defueling valve	1,2,5,6,7	Damage causes leak	1	3	3
Fuel System Post-Regulator	2	Fail to close manual valve	1	3	3
Fuel System Post-Regulator	2	Small Release	1	5	5
Fuel System Post-Regulator	1,2,3,4,5,6,7	Relief Valve Spontaneous Leak	1	2	2
Fuel System Post-Regulator	1,2,5,6,7	Damage causes leak	1	3	3
Hydrogen supply regulator assembly	1,2,3,4,5,6,7	Spontaneous Leak, Low pressure system exposed to high pressure	1	2	2
Hydrogen supply regulator assembly	1,2,5,6,7	Damage causes leak	1	3	3
Hydrogen venting tool	1	Premature disconnect	2	3	6
Hydrogen venting tool	1	Ignition near outlet	1	4	4
Hydrogen venting tool	1,2,3,4,5,6,7	Spontaneous Leak	1	2	2
Hydrogen venting tool	1,2,5,6,7	Damage causes leak	1	3	3
Automatic Shutoff Valve	1,2,3,4,5,6,7	Spontaneous Leak	1	2	2
Automatic Shutoff Valve	1,2,5,6,7	Damage causes leak	1	3	3
High-Pressure Defueling Tool	1	Premature disconnect	3	2	6
High-Pressure Defueling Tool	1	Ignition near outlet	1	4	4
High-Pressure Defueling Tool	1,2,3,4,5,6,7	Spontaneous Leak	1	2	2

Garage Geometry

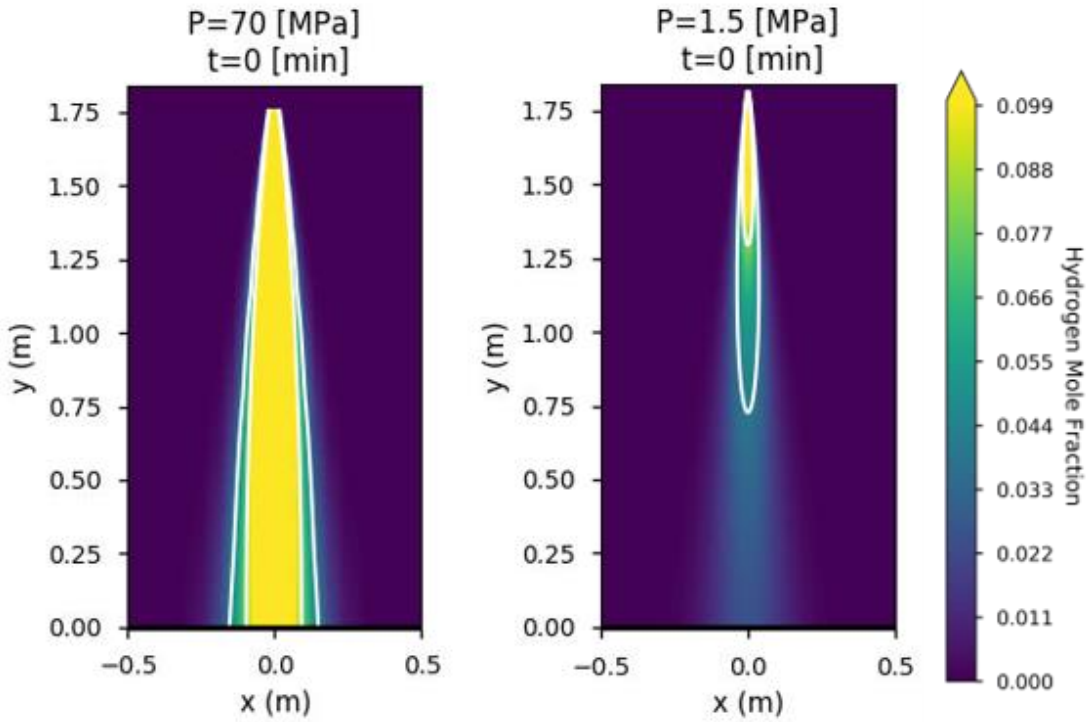




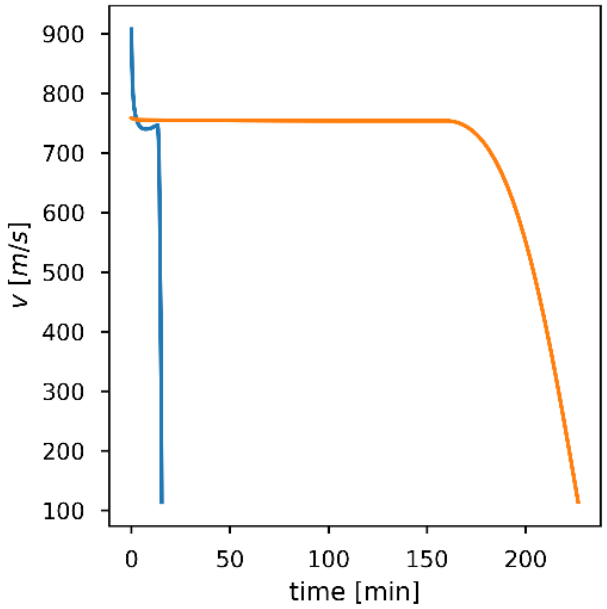


Analysis of Hydrogen Leak Velocity

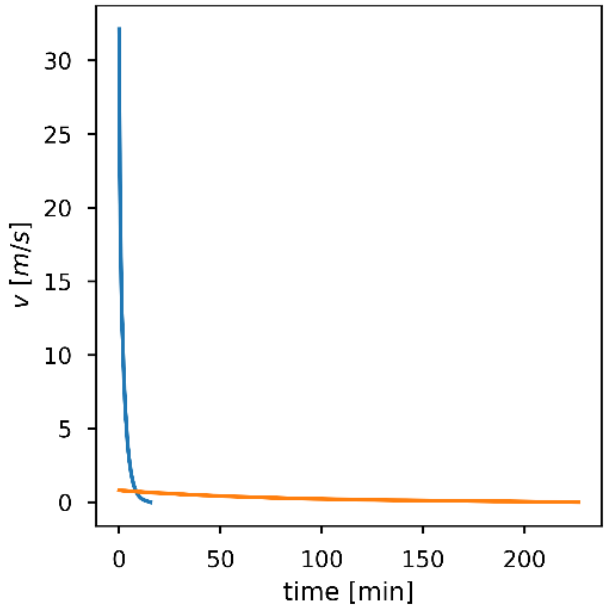
- CFD simulations rely on low-velocity gas flow
  - Flammable concentration does not reach floor for low-pressure release
  - May need to model differently for high-pressure releases in the future



MassTran Hydrogen Leak Velocity Comparison



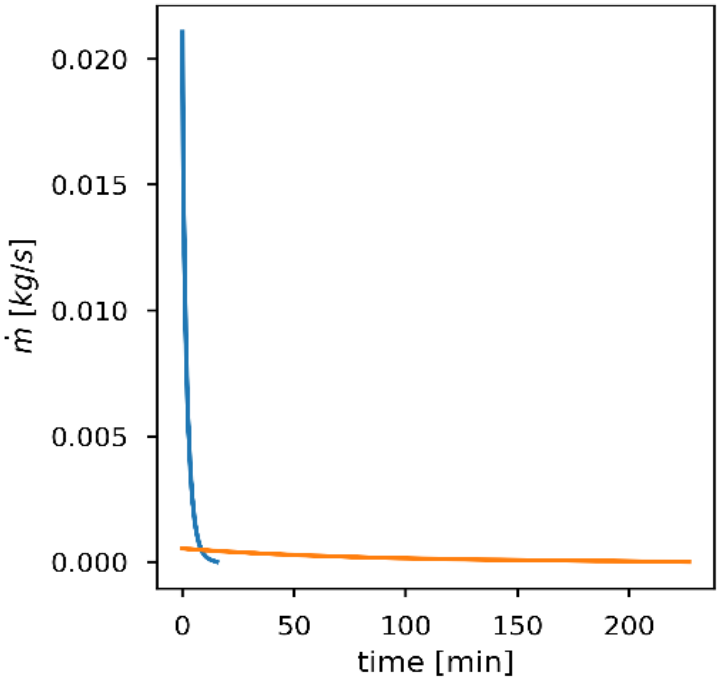
0.86 mm orifice



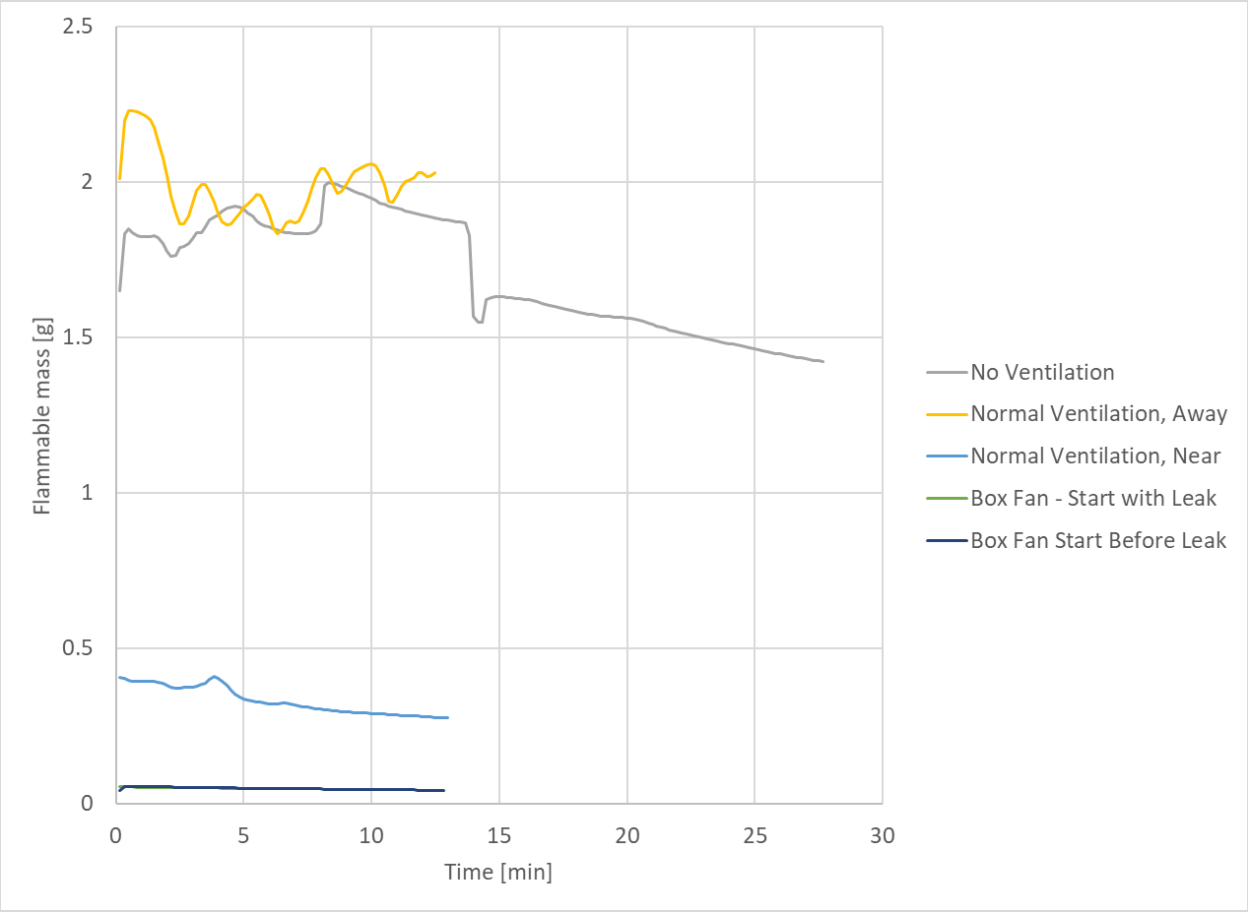
Alternative Subsonic Inlet (ASI)
10 cm orifice

Leak Flow Rates

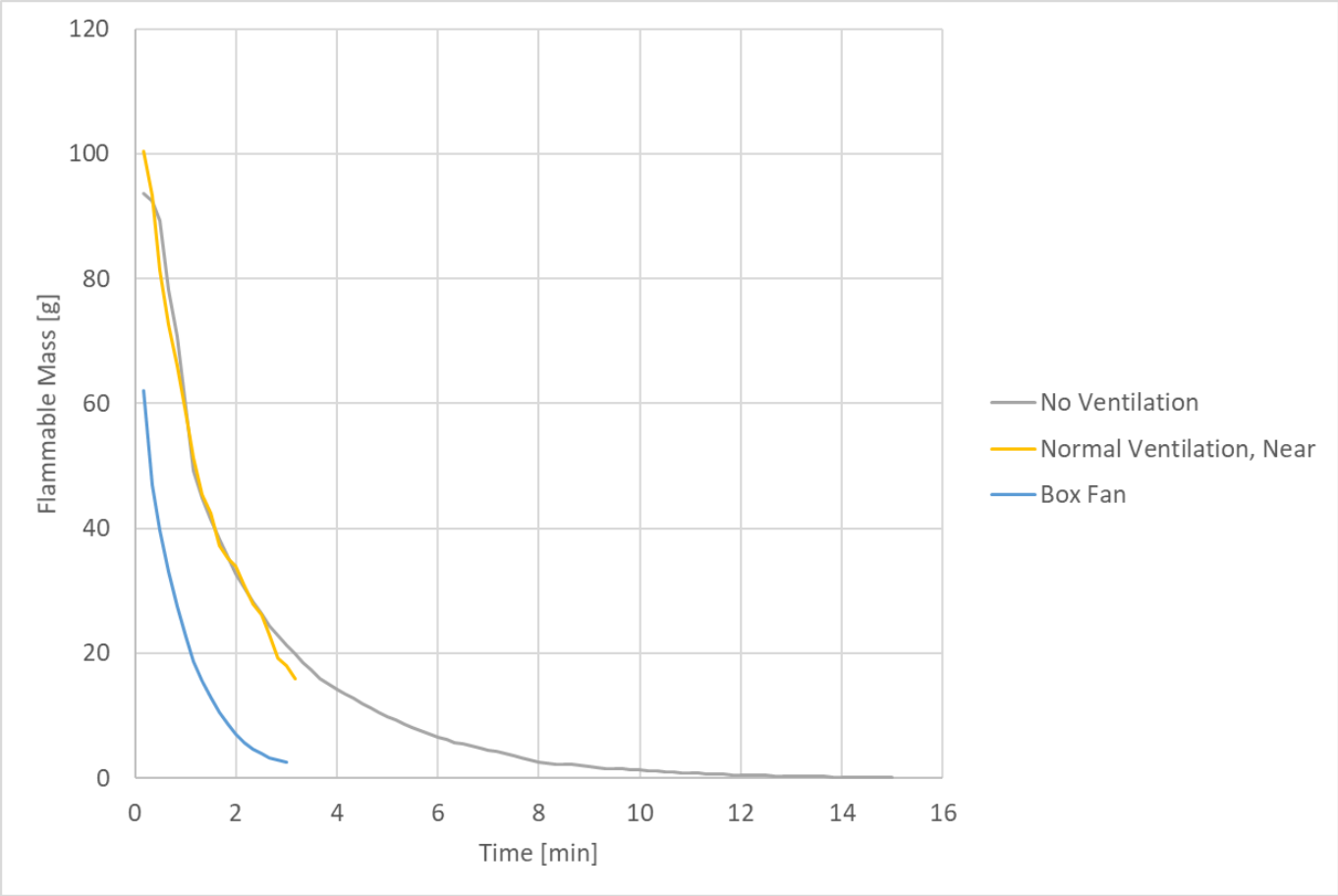
- MassTran modeling of flow rates



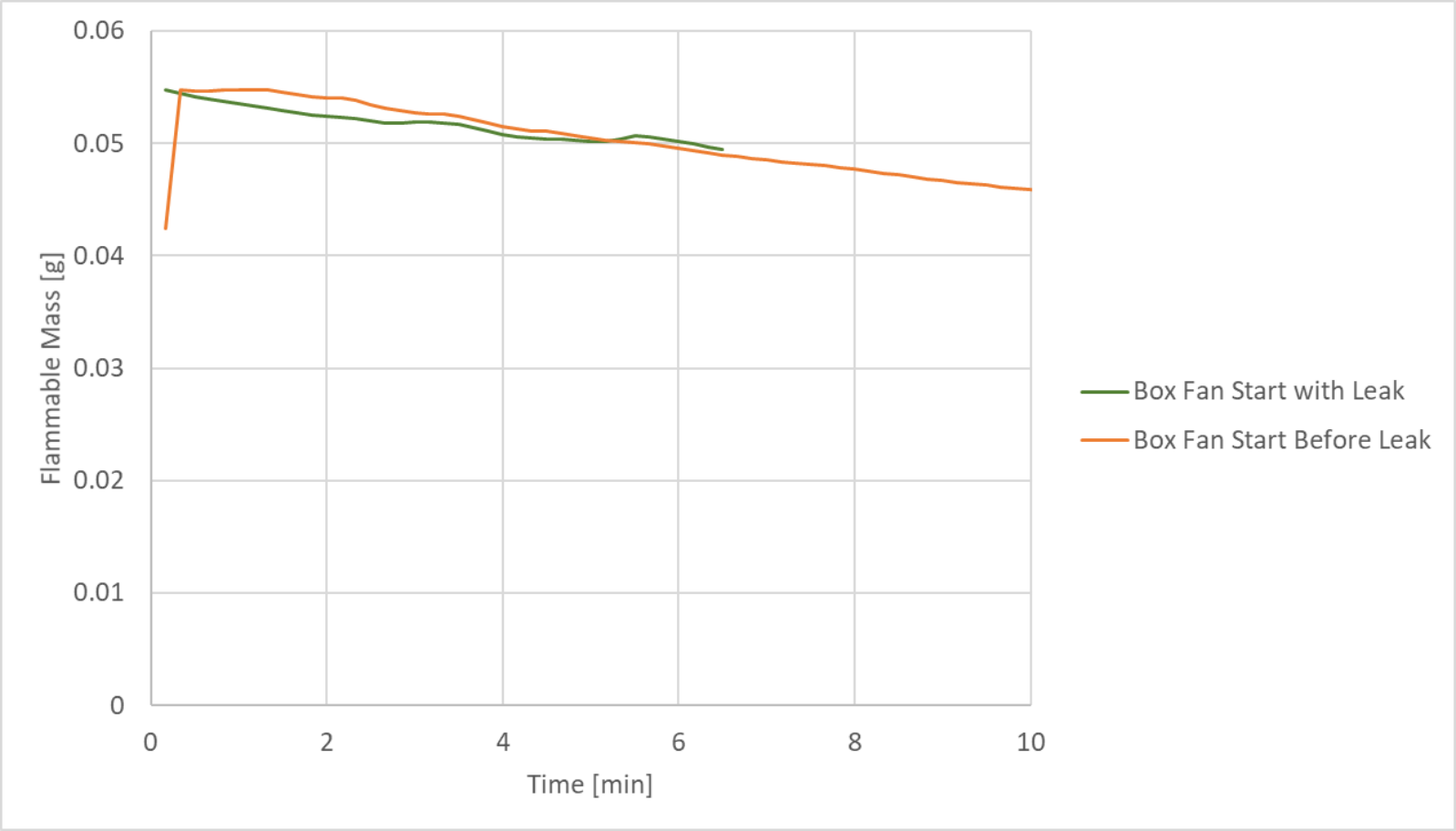
Flammable Mass over Time for Low Pressure



Flammable Mass over Time for High Pressure



Box Fan Start Times



Plume Spreading