Experimental Study of Hydrogen Release Accidents in a Vehicle Garage

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Outline

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- Instrumentation
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  - *Natural Ventilation Configuration*
- Summary and Conclusions

Acknowledgments

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Objective and Approach

Objective

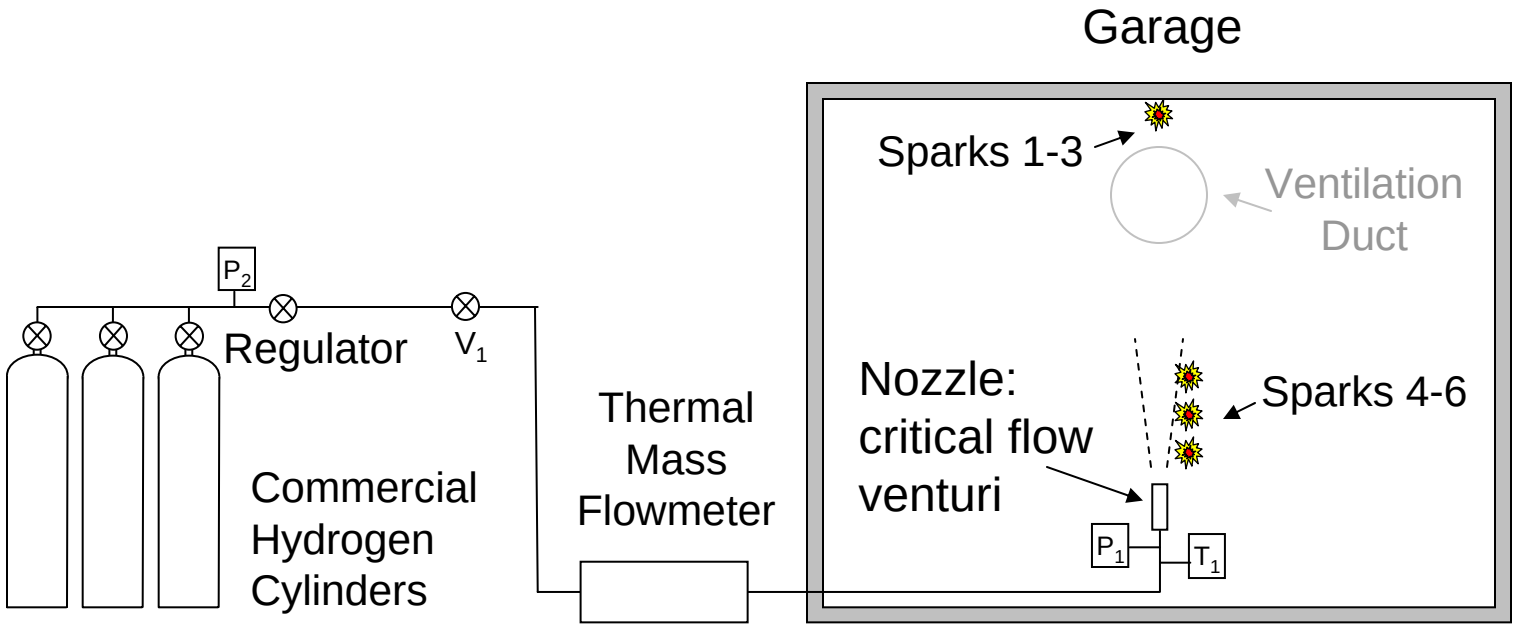
- Examine the risk and hazards involved with the deflagration of hydrogen releases in a one-car garage.

Approach

- Hydrogen release rates ranged from 0.88 kg/hr to 9 kg/hr.
- Hydrogen releases lasting 20 to 40 min. were studied using natural ventilation or mechanical ventilation (0.1 m^3/s - 0.4 m^3/s, 6 - 24 enclosure volumes per hour).
- The hydrogen concentration levels were measured, followed by the ignition of the flammable gas mixture.
- Flame speed and overpressure were measured to characterize the resulting deflagration.
- Two tests were performed with a vehicle inside the garage using the natural ventilation configuration.

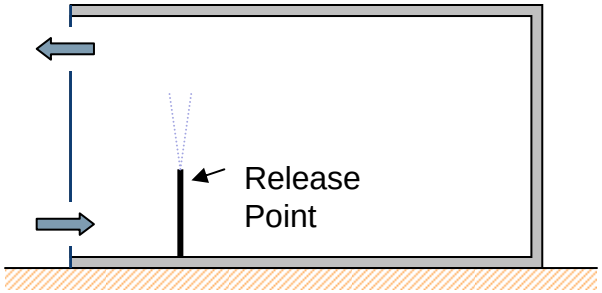
Garage Facility and Release Configuration

- Inside dimensions: 6.10 m x 3.64 m x 2.72 m
- The facility was constructed of reinforced steel.
- The hydrogen release rate and ventilation rates were nearly constant.
- Spark ignition modules were located on the ceiling and next to the release.



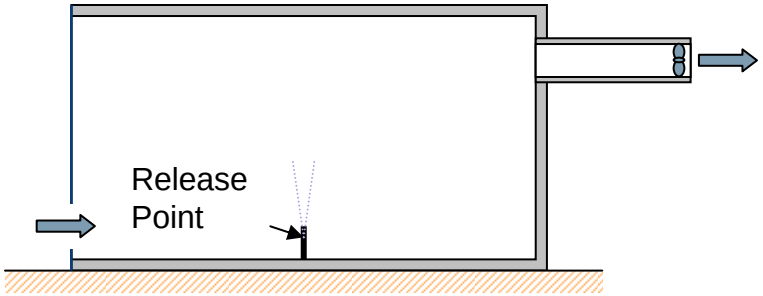
Ventilation Configuration

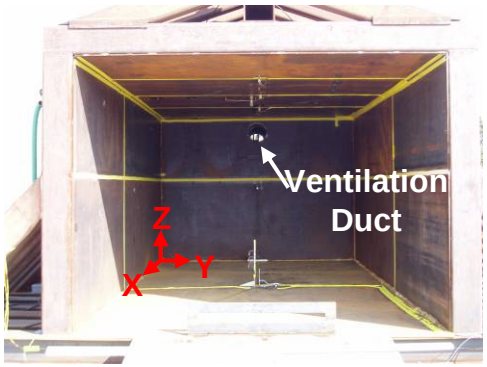
Natural Ventilation



Sized to meet upper and lower opening recommendations specified in the 2002 ICC Final Action Agenda, 0.046 m^2 open area per 28.3 m^3 of garage volume (½ ft^2 per 1000 ft^3)

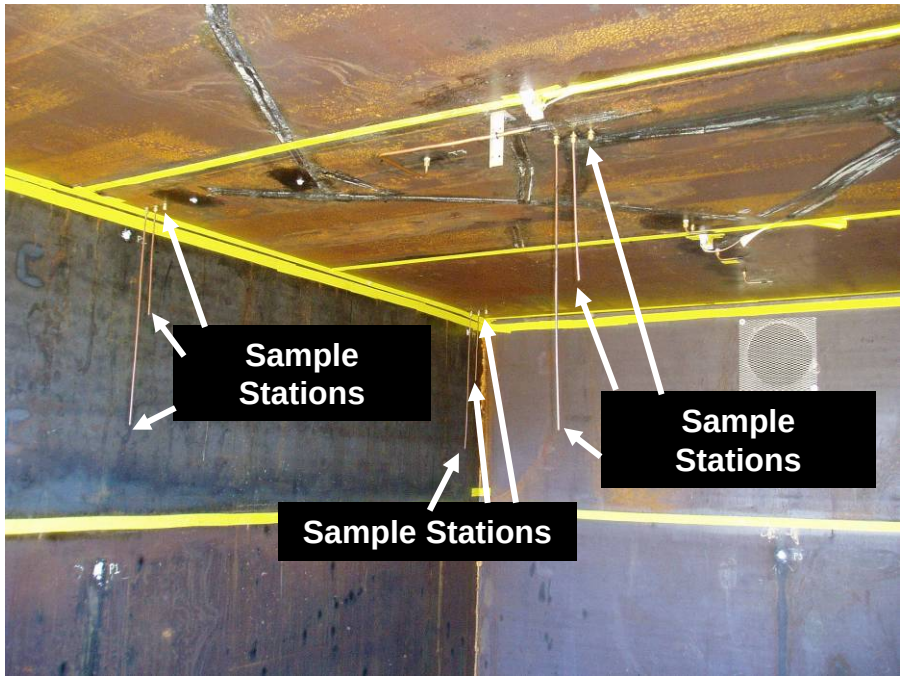
Mechanical Ventilation

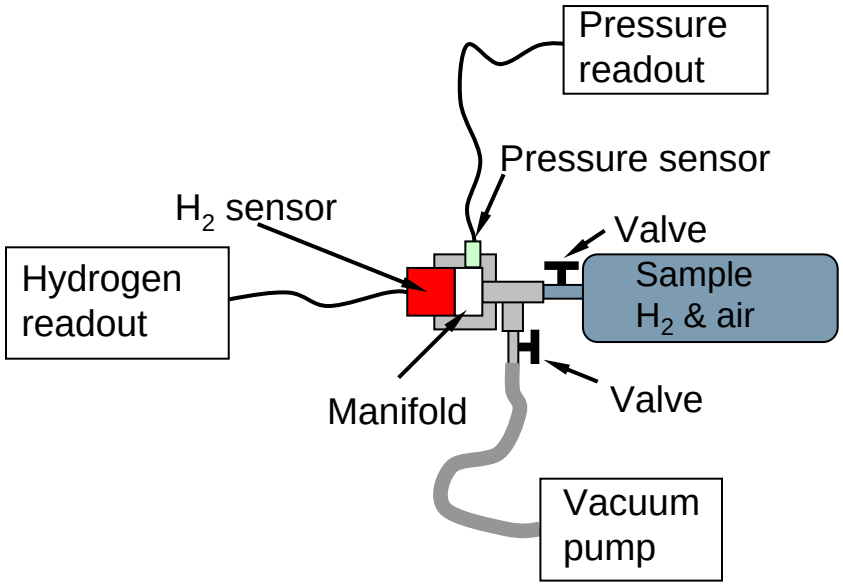




Concentration Measurements

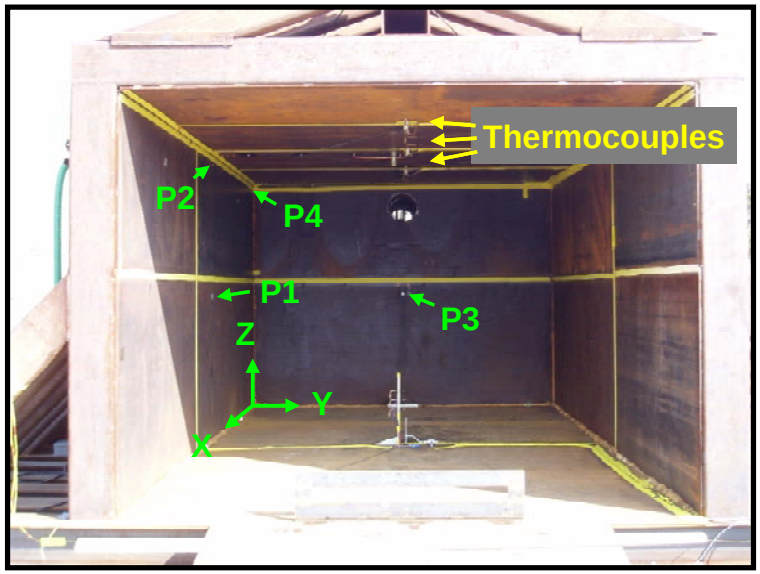
- A system of evacuated sampling bottles was used to measure hydrogen concentration at various points throughout the garage.
- The sample bottle concentration was measured after each test using an H2Scan palladium-nickel variable-resistance hydrogen sensor.



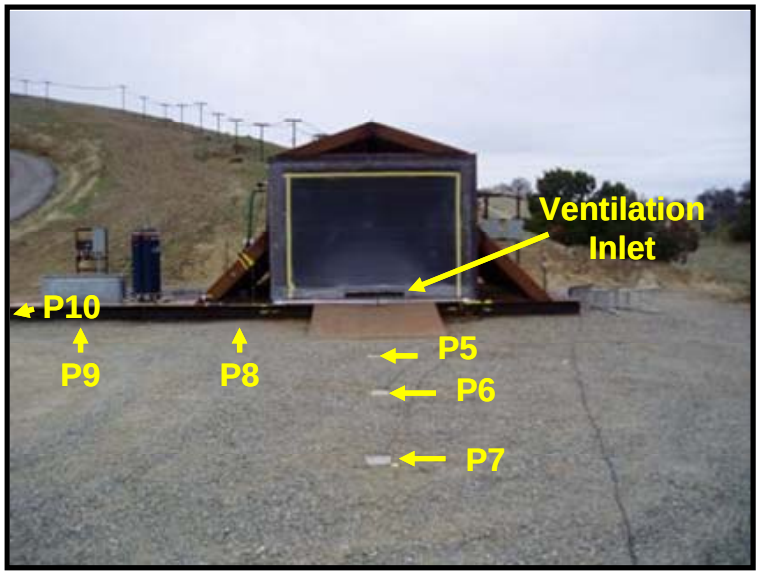


Instrumentation

Interior



Exterior



- Flame Front Detection
  - *Fast response thermocouples were used to measure the flame front time-of-arrival (TOA) and to determine the location of the ignition.*
- Pressure Transducers
  - *The blast overpressure generated within the garage was measured using four pressure transducers mounted on the inside walls.*
  - *Six free-field pressure transducers were used to measure the overpressures outside the garage.*

Jet Release Momentum

- The concentration profiles inside an enclosure are influenced by magnitude of:
  - Release momentum
  - Buoyancy forces
- Vertical stratified ceiling layers can form when buoyancy forces dominate [Baines & Turner].
- When momentum forces are dominant, overturning of the gas can lead to the development of a well-mixed ceiling layer
- The distance over which the momentum forces play a critical role, L_m, has been given by Morton as:

$$L_m = 0.63\alpha^{-1/2}\frac{M_o^{3/4}}{F^{1/2}}$$

α is the plume entrainment coefficient, taken to be 0.09

Buoyancy flux $$F = w_o g\pi\left(\frac{\rho_a - \rho_{H_2}}{\rho_a}\right)\cdot\left(\frac{D_o}{4}\right)$$

Release momentum $$M_o = w_o \pi D_o^2 / 4$$

$$L_m = 0.96 w_o \sqrt{\frac{D_o \rho_a}{g(\rho_a - \rho_{H_2})}}$$

- L_m has been calculated for ambient conditions.
- Release rates ≥1.5 kg/hr momentum forces were dominant when the release plume reached the ceiling at 2.72 m.
- Indicates that overturning will occur near the ceiling and that a well-mixed ceiling layer is likely to be formed.

Baines, W.D. and Turner, J.S., Turbulent buoyant convection from a source in confined region, *Journal of Fluid Mechanics*, 37, 1969, pp. 51-80.

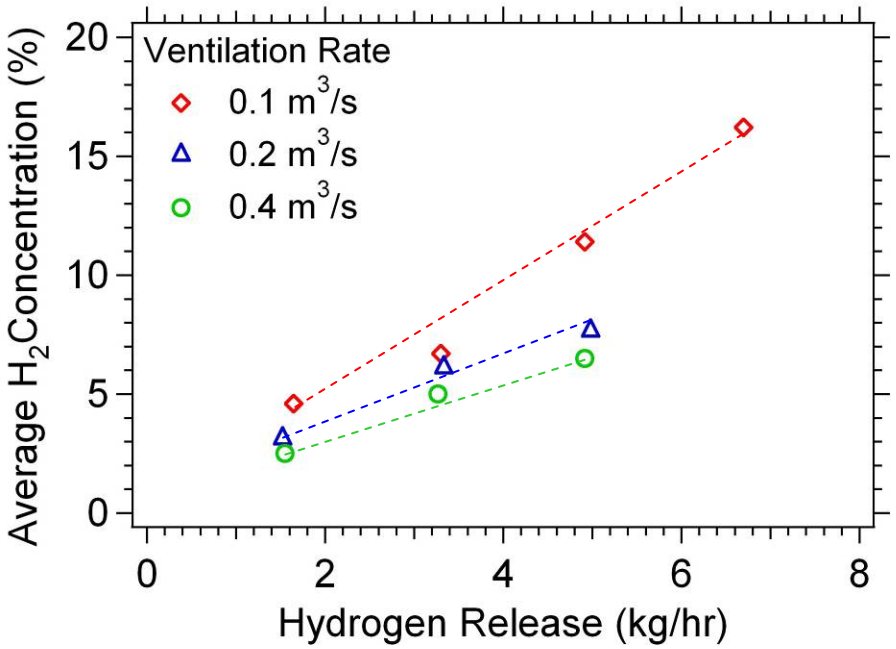
Morton, B.R., Forced plumes, *Journal of Fluid Mechanics*, 5, 1959, pp. 151-163.

Turner J.S., Buoyant plumes and thermals, *Annual Reviews of Fluid Mechanics*, 1, 1969, pp.29-44.

Mechanical Ventilation Tests

Test No.	Garage Interior	H_2 Release Rate (kg/h)	H_2 Mass Released (kg)	Release Duration	Ventilation
Mechanical Ventilation					
4	Empty	3.30	2.20	40 min	0.12 m^3/s
5	Empty	3.33	2.22	40 min	0.19 m^3/s
6	Empty	3.27	2.18	40 min	0.42 m^3/s
7	Empty	6.70	4.47	40 min	0.10 m^3/s
8	Empty	1.65	1.10	40 min	0.10 m^3/s
9	Empty	1.52	1.01	40 min	0.20 m^3/s
10	Empty	1.55	1.03	40 min	0.38 m^3/s
11	Empty	4.92	3.28	40 min	0.10 m^3/s
12	Empty	4.98	3.32	40 min	0.19 m^3/s
13	Empty	4.92	3.28	40 min	0.38 m^3/s

Average Concentration in Garage Ceiling Layer



Mechanical Ventilation Configuration

- 6.7 kg/hr release
  - *Overpressure generated was well below a level that would cause eardrum rupture.*
  - *Overpressure could potentially launch projectiles.*
- ≤4.9 kg/hr release
  - *Overpressures that resulted were very low and did not represent a risk to people or property.*
  - *Primary hazard was the deflagration of the hydrogen and air mixture and the burning of the hydrogen jet fire inside the garage.*

Natural Ventilation Tests

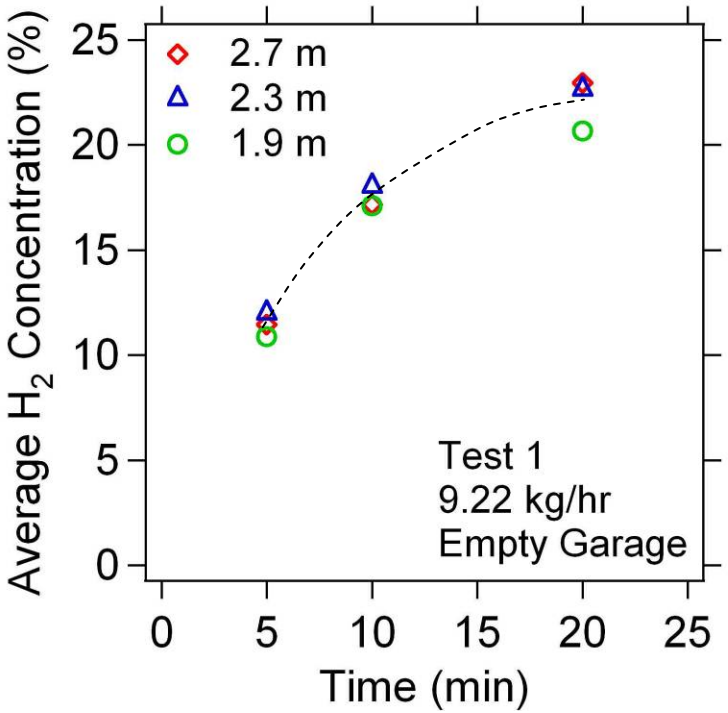
Test No.	Garage Interior	H_2 Release Rate (kg/h)	H_2 Mass Released (kg)	Release Duration	Ventilation
Natural Ventilation					
1	Empty	9.22	3.07	20 min	Natural
2	Vehicle	9.04	3.01	20 min	Natural
3	Vehicle	0.88	0.44	30 min	Natural

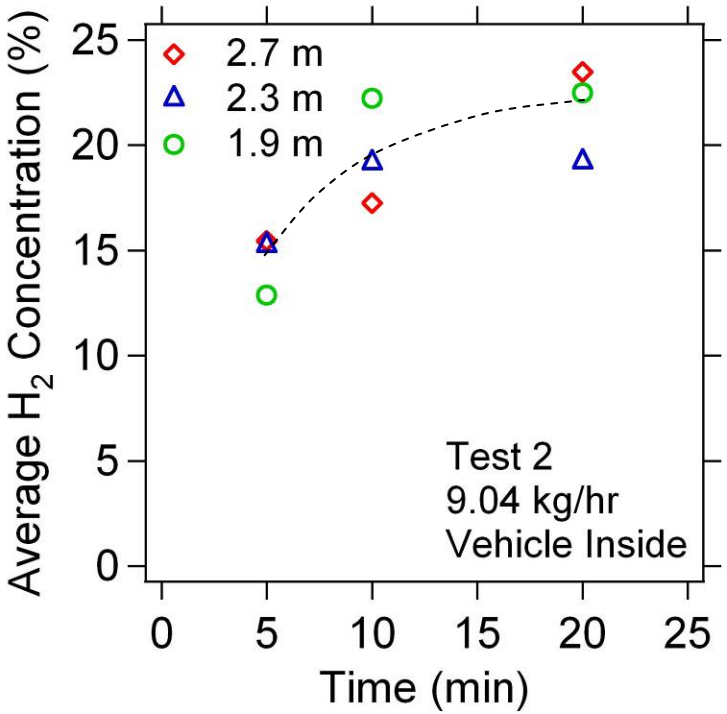
- Two tests were conducted to evaluate what effect a vehicle inside the garage would have on hydrogen concentrations and any resulting combustion.
- The vehicle was a Ford Explorer with dimensions similar to a potential future fuel-cell vehicle.

Hydrogen Concentration Measurements

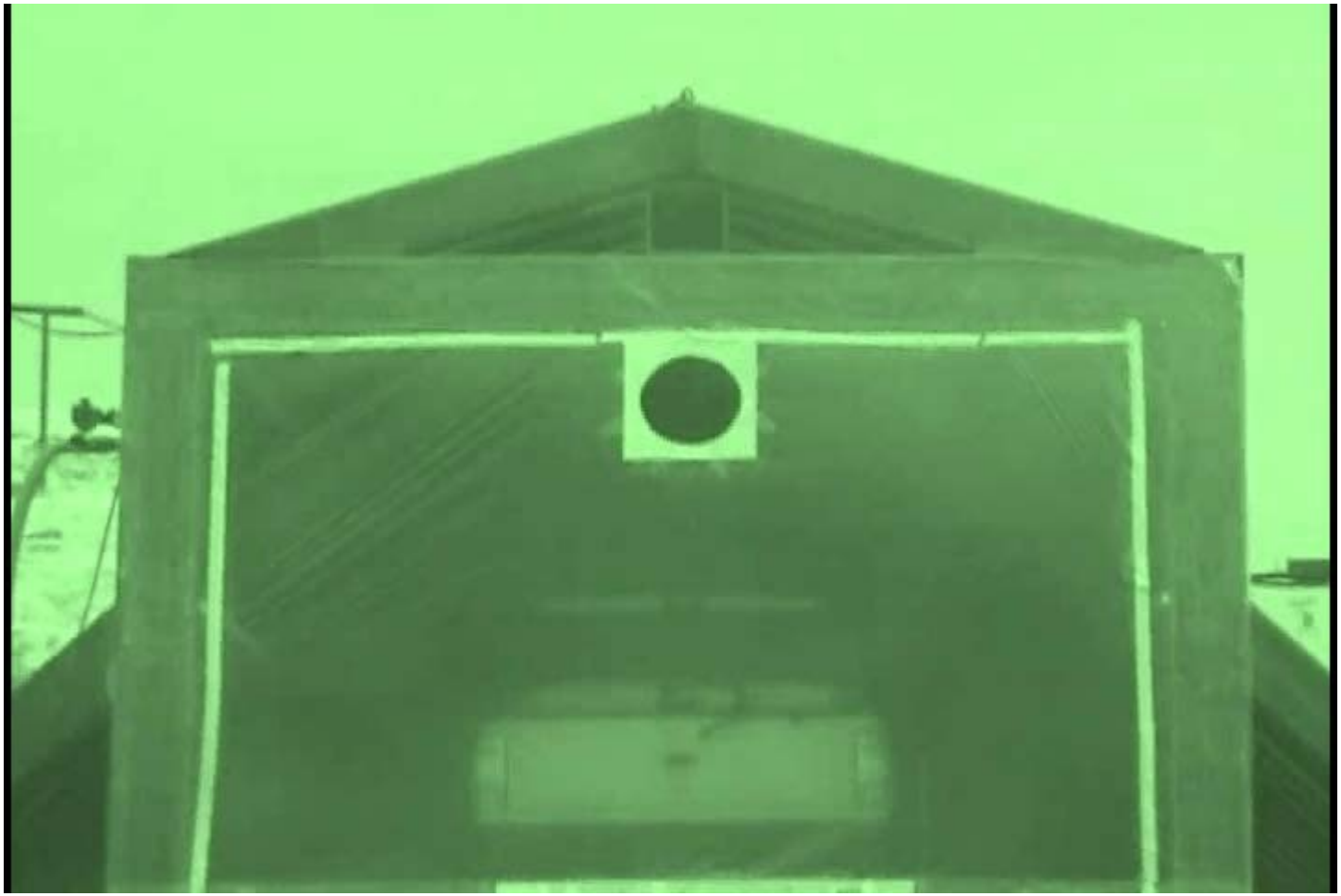
9 kg/hr releases

Hydrogen concentrations at the top of the garage were similar at the time of ignition for the test with an empty garage and the test with a vehicle inside.



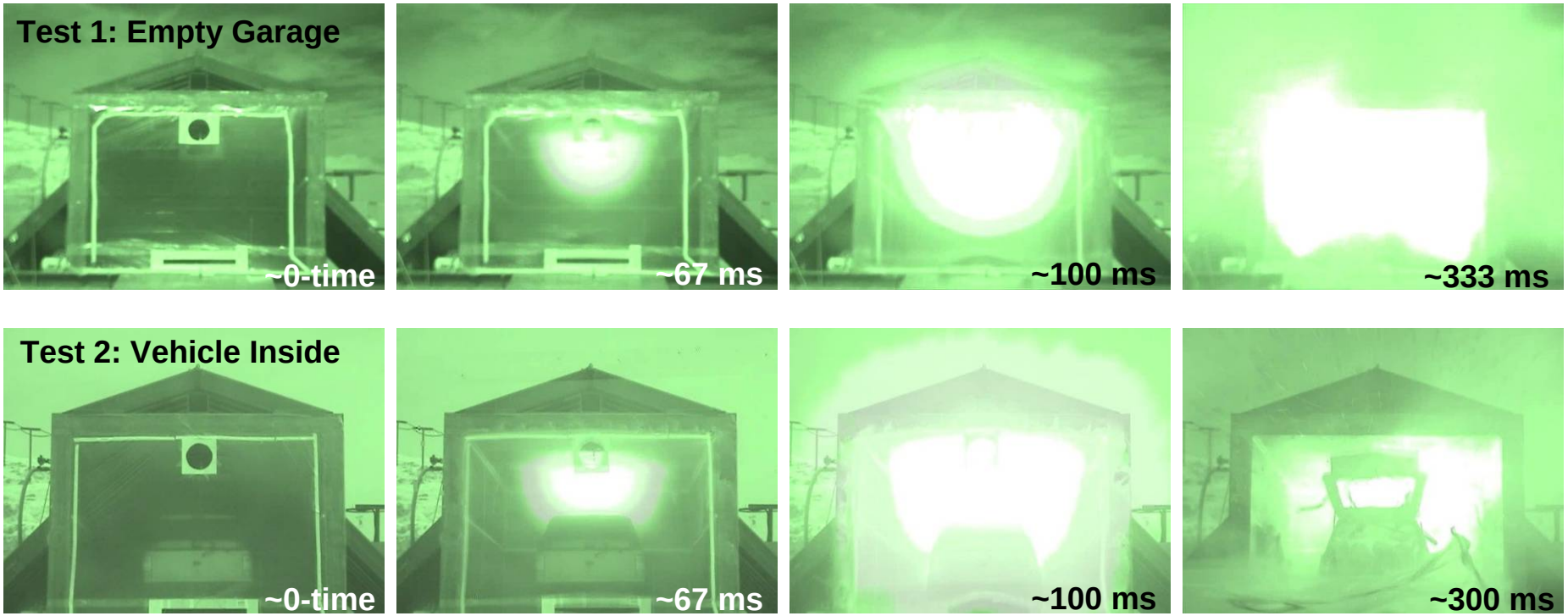


Vehicle Inside Garage with a 9 kg/hr Release



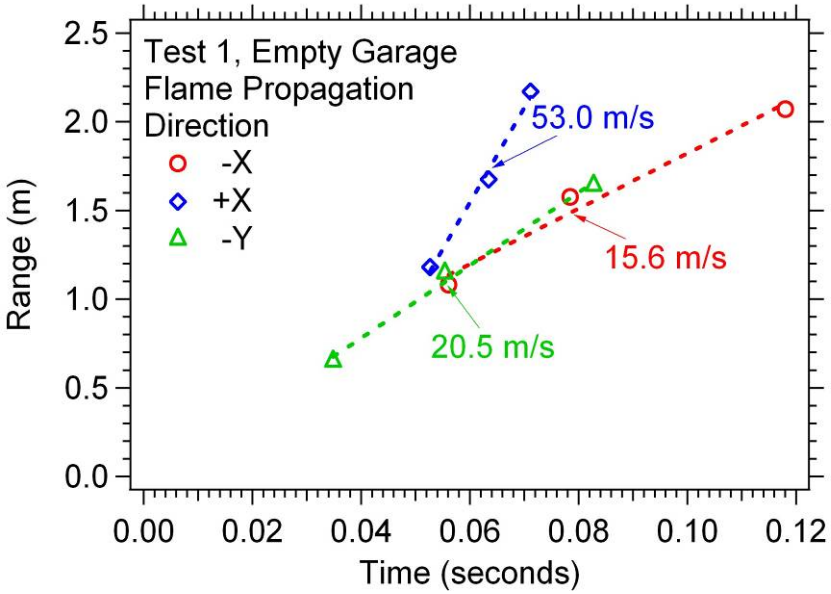
Infrared Video

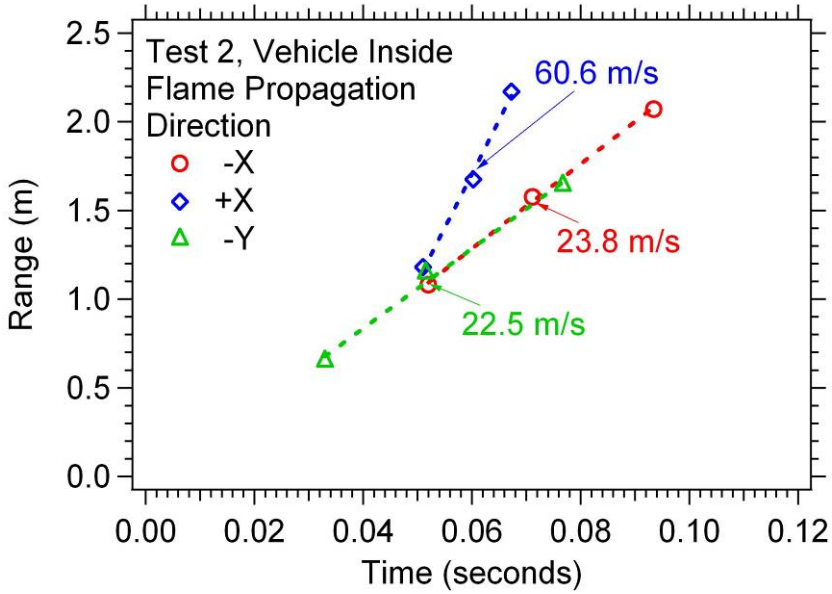
9 kg/hr release with an empty garage vs. with a vehicle inside



Flame Front Propagation and Flame Speed

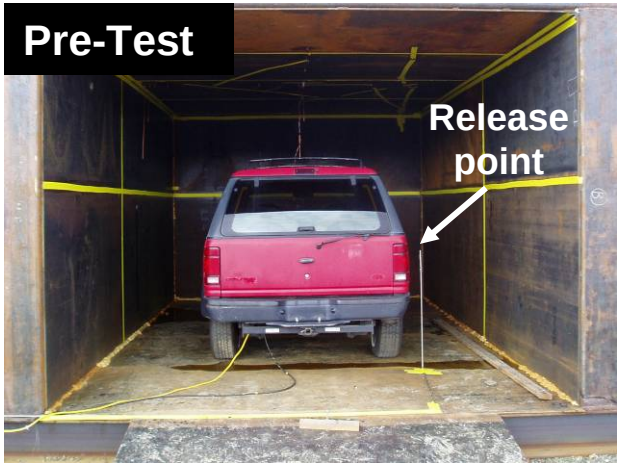
- There was a small increase in flame speed when the vehicle was present.
  - *Probably caused by the vehicle-created blockage inside the garage*
- The enhancement of the deflagration caused by the external surface of the vehicle appears to be small.

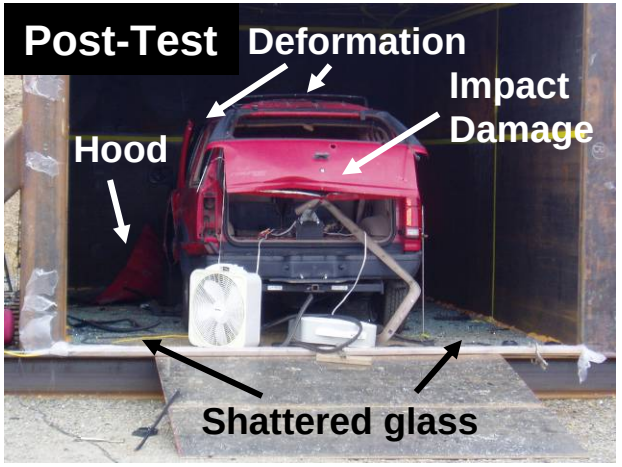


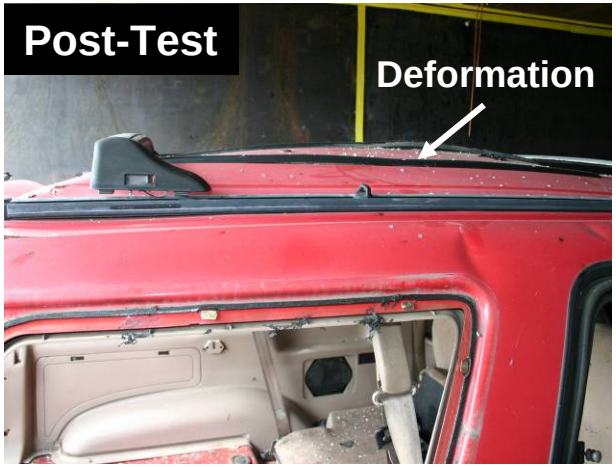


Vehicle Damage

- Internal explosion occurred within the engine compartment and inside the cabin.
- The deflagration did not set the vehicle or any of its components on fire.

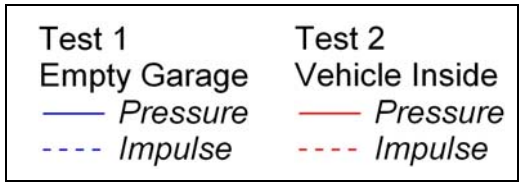


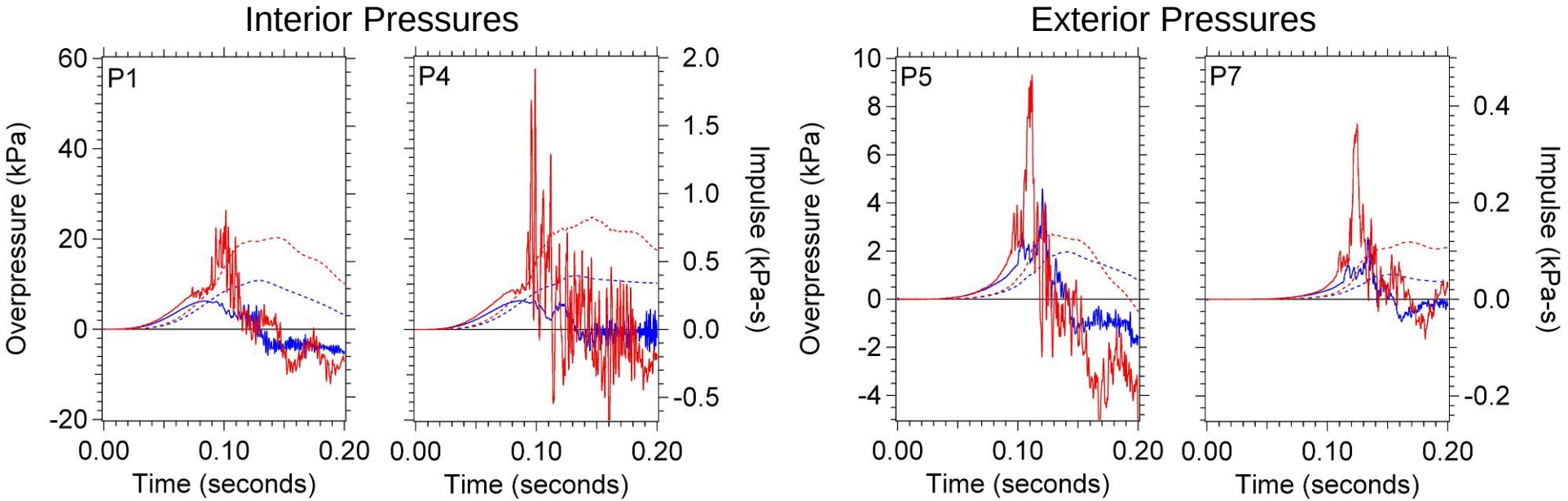




Overpressure and Impulse

- A sudden increase in overpressure occurred about 0.085 s after ignition when the vehicle was inside the garage.
  - *Can be attributed to the enhancement of the deflagration as it propagates through the congested region inside the engine compartment and inside the cabin of the vehicle*





Summary and Conclusions

- All the release scenarios resulted in well-mixed lean mixtures below the ceiling.

Mechanical Ventilation Configuration

- ≤ 4.9-kg/hr release
  - *Primary hazard was the deflagration of the hydrogen and air mixture and the burning of the hydrogen jet fire inside the garage.*
  - *Overpressures were very low and did not represent a hazard to people or property.*
- 6.7-kg/hr release
  - *Overpressure generated was well below a level that would cause eardrum rupture.*
  - *Overpressure could potentially launch projectiles.*

Natural Ventilation Configuration

- 0.88-kg/hr release (with vehicle)
  - *Ignition occurred above the release point, and the flame slowly propagated across the ceiling.*
  - *No overpressure was detected.*

Summary and Conclusions (cont.)

Natural Ventilation Configuration (cont.)

- 9 kg/hr release (no vehicle)
  - *Flame speeds between 16 and 53 m/s were measured on the ceiling.*
  - *Overpressure generated was below a level that would cause eardrum rupture.*
- 9 kg/hr release (with vehicle)
  - *Slight increase in flame speed near ceiling when compared with the no-vehicle test*
  - *Significant overpressures were generated due to the vehicle presence: they were tripled inside the garage and doubled outside the garage.*
    - Interior overpressures were of a magnitude where ear drum damage could be a concern.
    - Most likely due to turbulent enhancement created by the congested region and confinement inside the vehicle.
  - An internal explosion occurred within engine compartment and inside cabin shattering glass and launching projectiles
    - *The buoyant ceiling layer probably extended below the hood of the car and collected inside the vehicle*

The internal geometry of the vehicle needs to be taken into account when modeling this type of accident scenario.

Thank You!

Questions?