Effect of aircraft extinguishing agents on various flammable gases

Federal Aviation Administration

Triennial presentation

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Background/Motivation

- There have been numerous aircraft accidents and incidents involving lithium batteries on aircraft.
- There is a lack of knowledge of the effectiveness of various extinguishing agents on aircraft.
- Information in this field can promote safety by giving airlines and airframe manufacturers sufficient data to make informed decisions about how to safely transport lithium batteries.

Background – Battery Fires

- **The main source of fuel for lithium battery fires is generally the flammable gases generated from thermal runaway.**
  - Flammable battery gas composition can vary due to many factors including State-of-Charge, Chemistry, and overall design.
  - Three main flammable gases:
    - Hydrogen
    - Hydrocarbons
    - Carbon Monoxide
  - Among the 3 gases, composition variations can seem endless, especially due to the broad variety of hydrocarbons that can exist.

Extinguishing agents on aircraft

- **Current:**
  - Halon 1301 (CF_3Br)
- **Potential:**
  - 2-BTP/CO_2 (mixed 50/50 by weight), ($C_3F_2H_3Br$ / CO_2)
  - Carbon Dioxide
  - Nitrogen
  - Aerosols

Introduction – criteria for flammability of gases/inerting concentrations of agents

- **Experimental:**
  - Upward flame propagation
  - Downward flame propagation
  - Pressure rise
  - Heptane cup burner
  - Others
- **Computational and Analytical**
  - Le Chateliers formula, extended Le Chateliers formula
  - Laminar flame speed (3 cm/sec to 5 cm/sec)
  - Adiabatic flame temperature (1400K to 1600K)
  - Additional “black-box” methods that were created without much regard to the theory of combustion, flame propagation and flame extinction.

$$LFL_{mix} = \frac{1}{\sum \frac{x_i}{LFL_i}}$$

Introduction – past studies of extinguishing agents

	Halon 1301	Carbon Dioxide	Nitrogen
Hydrogen	26.7% – 28.6%	56% – 61%	75%
Methane	6.2% - 7%	23.0% – 28.6%	36.7% – 40.6%
Ethylene	12%	41%	50%
Carbon Monoxide	n/a	53%	68%
Battery Gas	8.6%	n/a	n/a

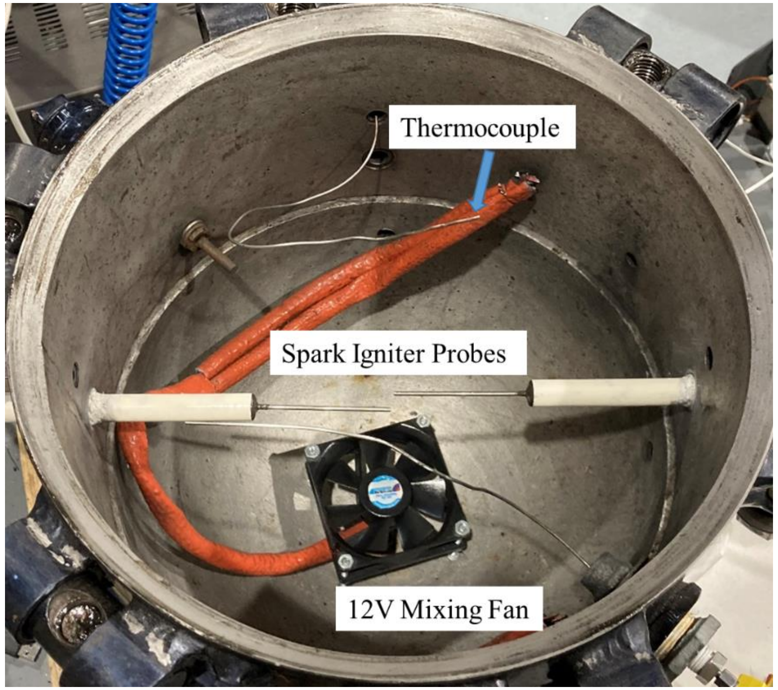
- Range of percentages due to variation in method used.

Objective

- **Evaluate the effectiveness of cargo compartment fire suppression agents against lithium battery fires and individual flammable gases.**
- **Evaluate the effectiveness of simulation methods and analytical methods at predicting the effectiveness of various extinguishing agents.**

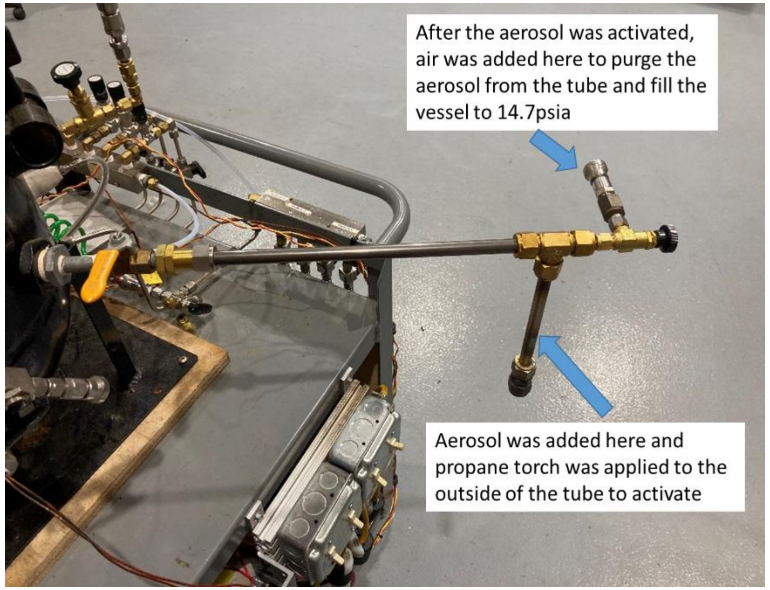
Setup

- **Simulations: Cantera**
  - Use mechanism files that were compiled previously by NIST
  - Use laminar flame speed and adiabatic flame temperature as a predictor of flammability
- **Experiments:**
  - 21.7 liter combustion sphere
  - Spark igniter for ignition (0.5 second duration, 10k volts, 5mm gap)
  - Small computer fan to mix gases
  - Piezo-electric pressure sensor (max pressure and max rate-of-pressure rise)



Aerosol

Pre-determined weight of agent



Method 1

Method 2

- **Two methods were used to add aerosol extinguishing agent to the vessel.**
  - Method 1: Aerosol chunks were placed in a stainless steel tube as shown and ignited by heating the outside with a torch.
  - Method 2: Aerosol chunks were placed between the two ignitor probes within the pressure vessel (within cellophane).

Gases

- **All other gases were extracted from bottles with specified purities.**

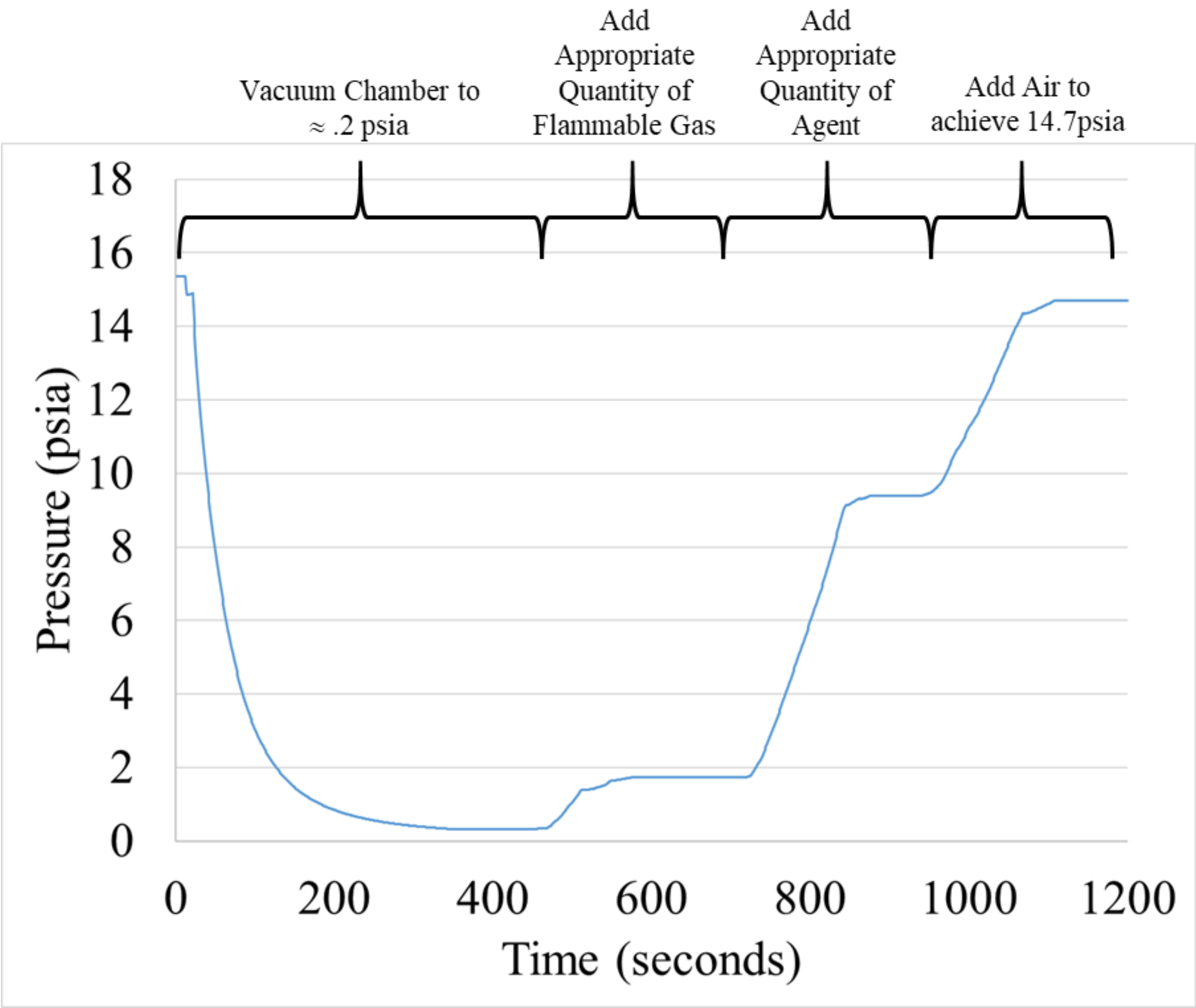
Air	Ultra Zero Grade
Hydrogen	99.999% Purity
Methane	99% Purity
Ethylene	99.5% Purity
Carbon Monoxide	99.5% Purity
Nitrogen	99.999% Purity
Carbon Dioxide	99.8% Purity
Halon 1301	Unknown Purity
2-BTP	Extracted from Handheld Extinguisher
Aerosol	A Solid that Creates an Aerosol Mixture when Activated

Gases used

Hydrogen	27.7%
Carbon Monoxide	22.9%
Methane	6.4%
Propylene	4.52%
Ethylene	2.19%
1-Butene	1.58%
Ethane	1.16%
Butane	.56%
Propane	.267%
Carbon Dioxide	30%
Nitrogen	balance

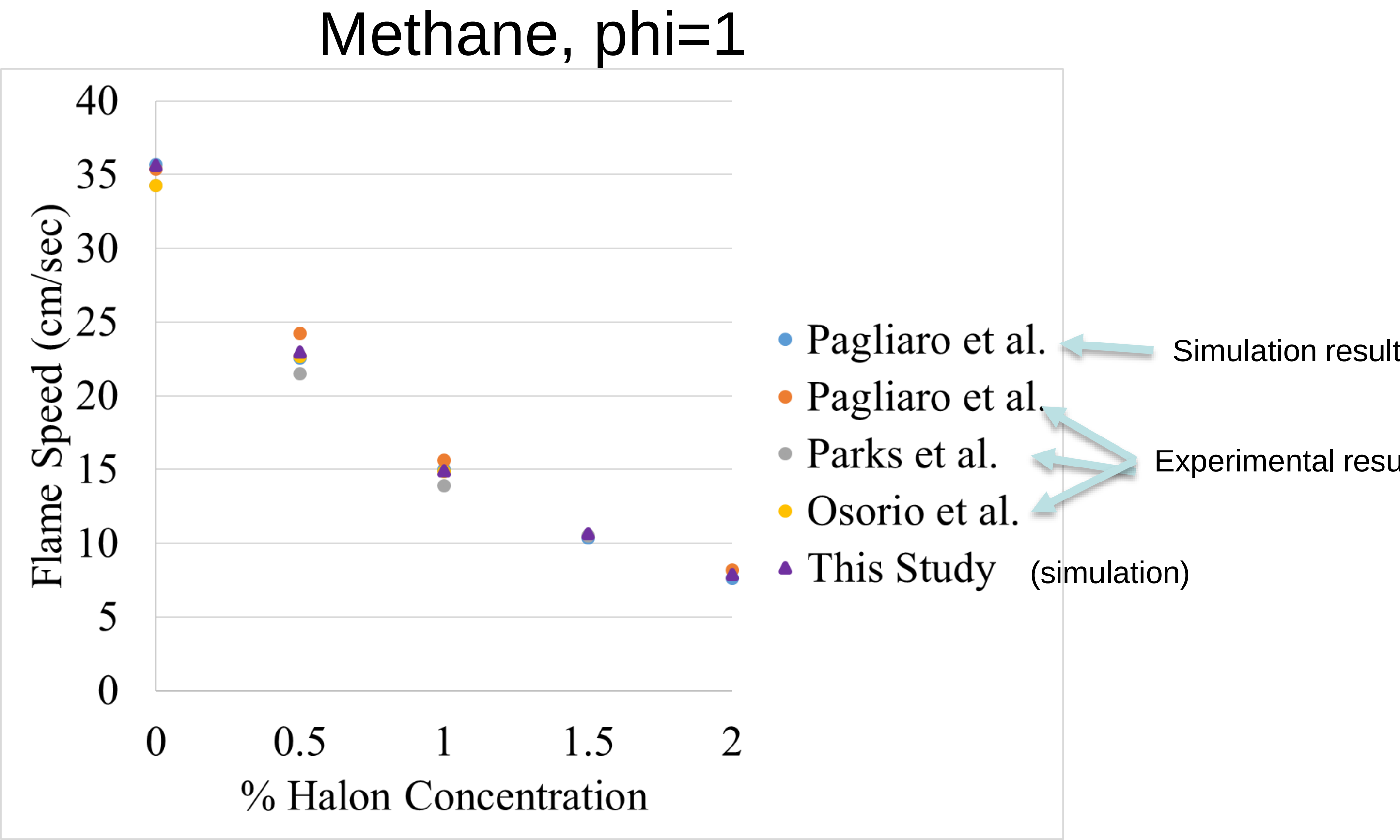
Battery gas mixture

Test Procedure



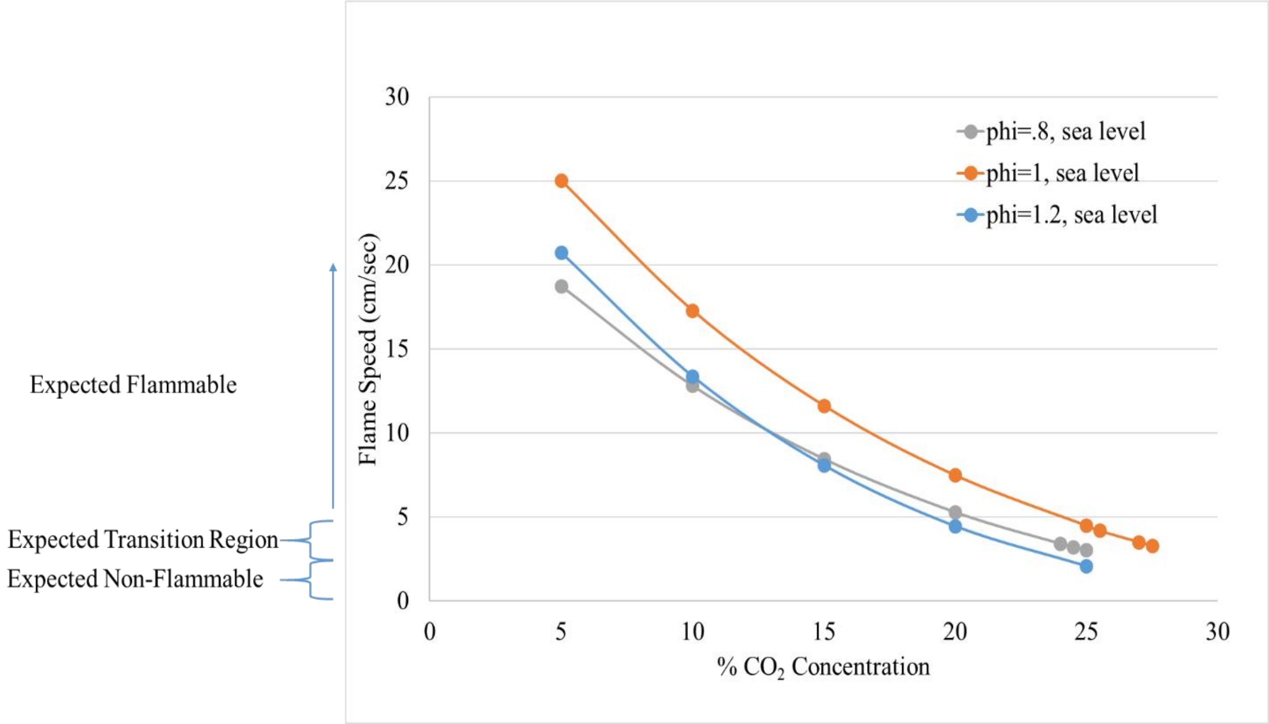
Cantera Setup

- **Once Cantera was loaded with kinetic, thermodynamic, and transport parameters from various sources, simulations were run to ensure results aligned with literature.**

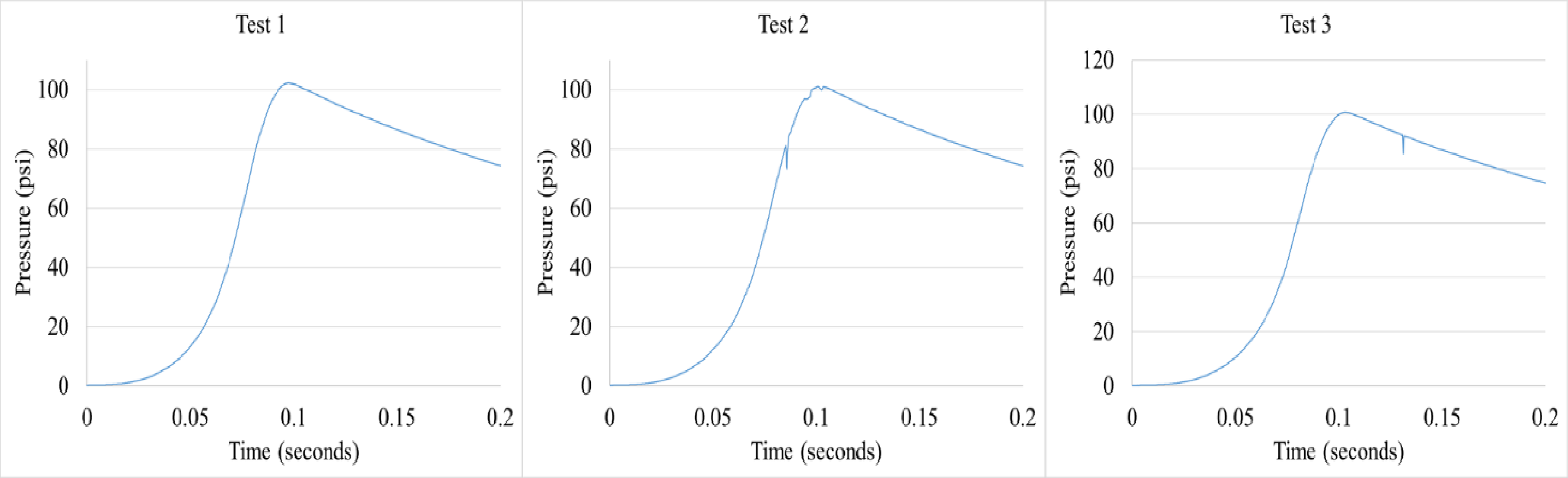


Using flame speed to predict a starting point for experiments

- **Cantera simulations were run during experimental down time to minimize the number of experiments required to find the flammability limits.**



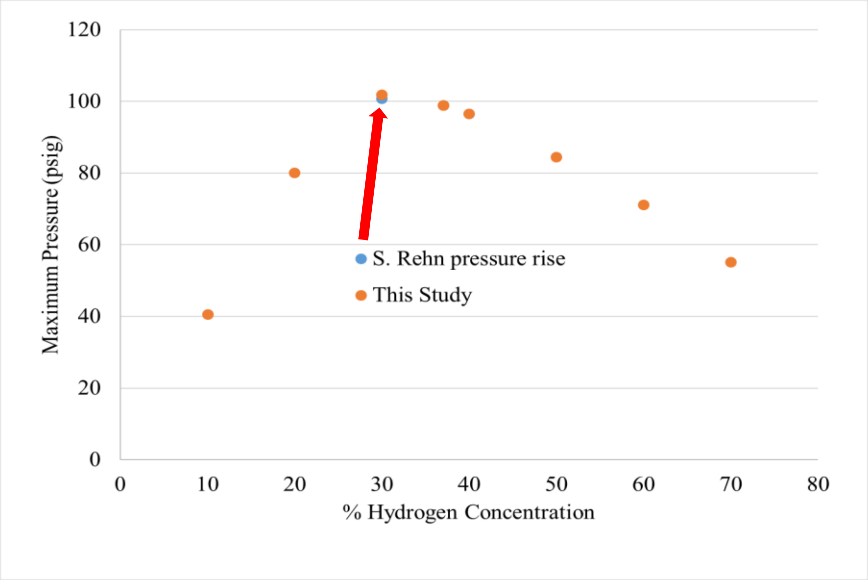
Pressure Rise Repeatability



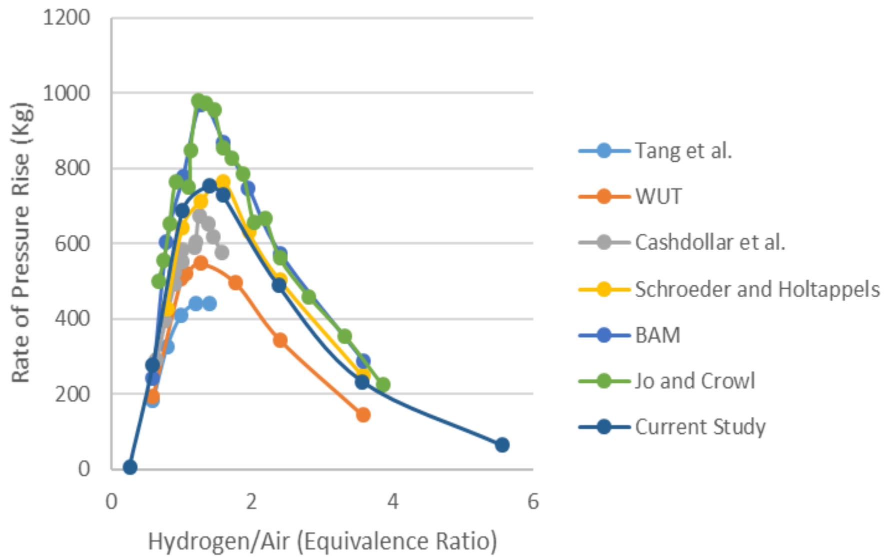
- **Repeatability experiments were performed to ensure peak pressure rise was repeatable.**

Comparison of pressure rise results to literature

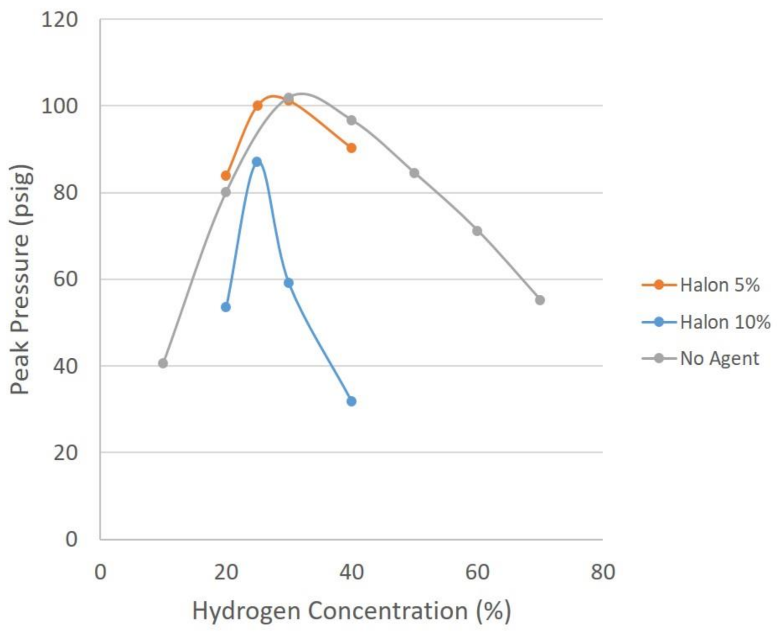
- **Peak pressure experiments were performed and compared to literature.**

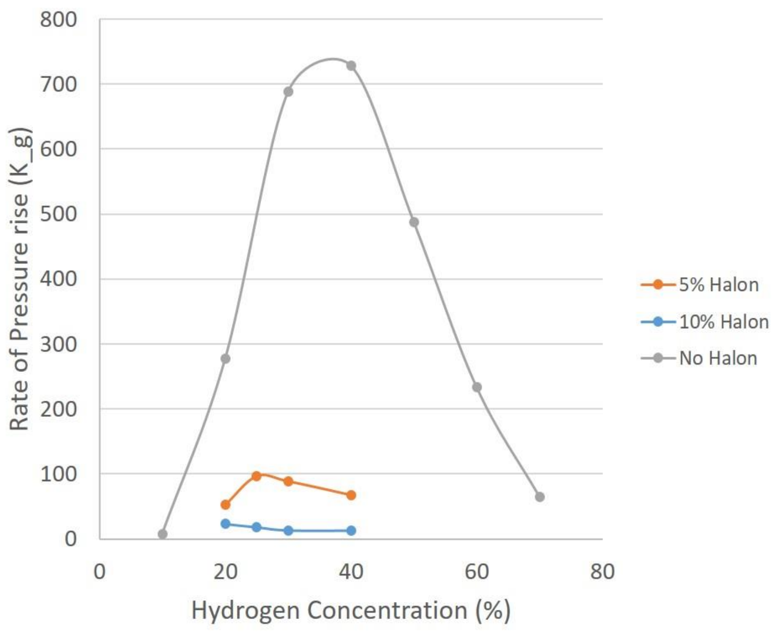


- **Rate-of-pressure-rise experiments were performed and compared with literature.**



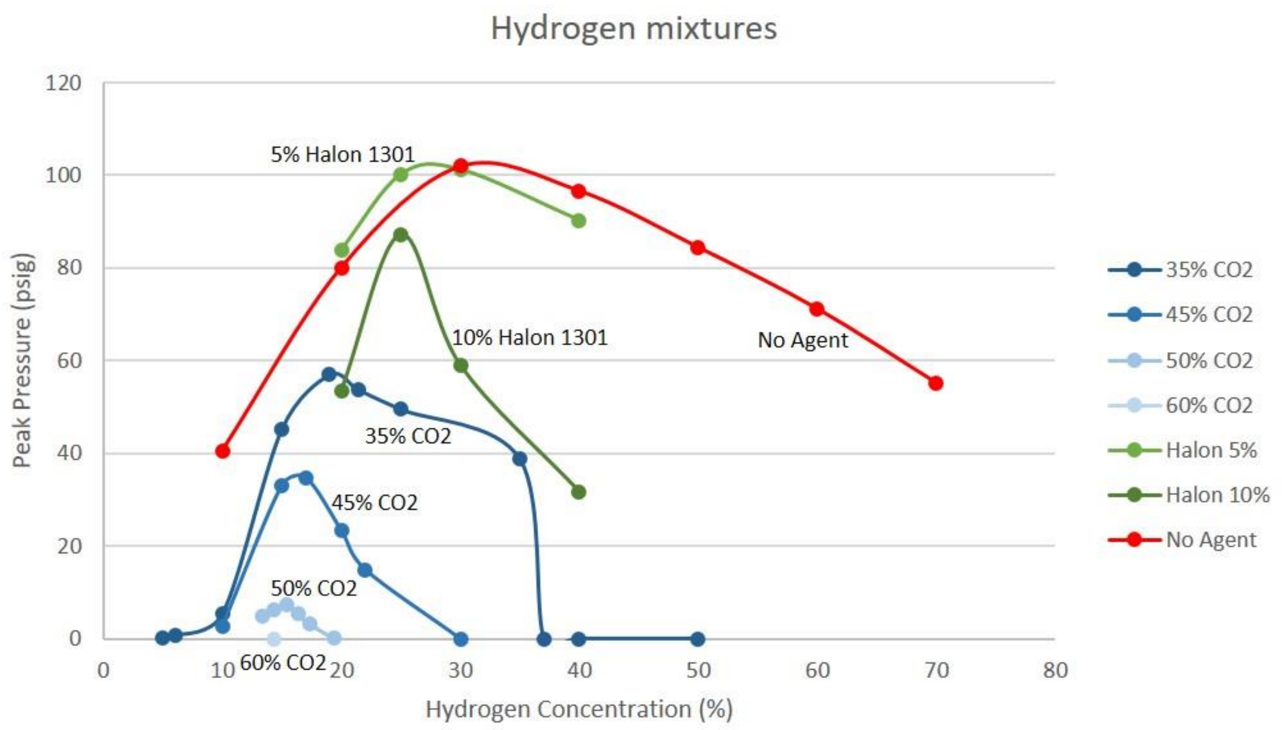
Initial testing – Halon and Hydrogen





- Lower concentrations of Halon 1301 can have little effect on peak pressure but significantly reduce rate of pressure rise.
- Correlates to a significant decrease in flame speed but a much less significant decrease in total heat release.

Initial testing – flammability curves

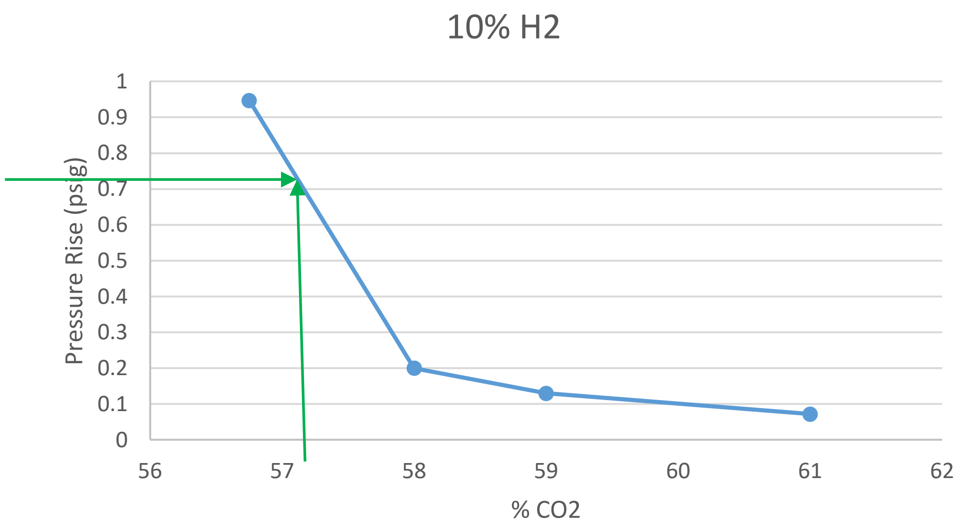


- Certain Halon 1301/hydrogen mixtures have a greater pressure rise than if no Halon 1301 was added.

LFL testing – flammability criteria

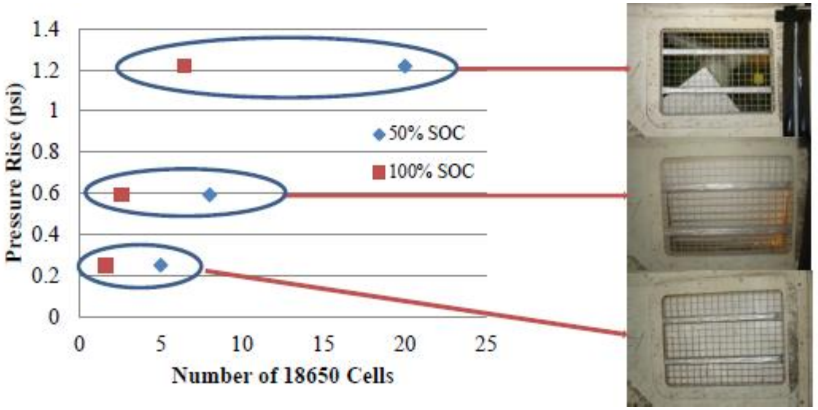
- **5% pressure rise criteria**
  - 0.735psi at sea level
  - About the pressure required to dislodge a cargo compartment decompression panel.

Example:



Interpolation to find values

Recall from previous work:



Test Plan

- **Experiments and simulations were performed according to the table below. The value in each cell denotes the equivalence ratio at which the test was performed.**

* *Simulations and Experiments* ** *Experiments only* ****Simulations only*	Nitrogen	Carbon Dioxide	Halon 1301	2-BTP/CO_2 Mix	Aerosol
Hydrogen	.8*, 1*	.8*, 1*	.8*, 1*	.8*, 1*	n/a
Methane	.8*, 1*	.8*, 1*	.8*, 1*	.8*, 1*	1**
Ethylene	.8*, 1*	.8*, 1*	.8*, 1*	.8*, 1*	n/a
Carbon Monoxide	.8*, 1*	.8*, 1*	.8*, 1*	.8*, 1*	n/a
Battery Gases	.8*, 1*	.8*, 1*	.8*, 1*	.8*, 1*	n/a
Hydrogen, 200℃	1***	1***	1***	1***	n/a
Methane, 200℃	1***	1***	1***	1***	n/a
Ethylene, 200℃	1***	1***	1***	1***	n/a
Carbon Monoxide, 200℃	1***	1***	1***	1***	n/a
Battery Gases, 200℃	1***	1***	1***	1***	n/a
Hydrogen, 25k feet altitude	n/a	n/a	1***	1***	n/a
Methane, 25k feet altitude	1***	1***	1***	1***	n/a
Ethylene, 25k feet altitude	1***	1***	1***	1***	n/a
Carbon Monoxide, 25k feet altitude	1***	1***	n/a	n/a	n/a
Battery Gases, 25k feet altitude	1*	1*	n/a	1***	n/a

Experimental Results, phi=1

Experimental results, phi = 1	**Nitrogen Required**	**Carbon Dioxide Required**	**Halon 1301 Required**	**2-BTP/CO_2 Mix Required**
Hydrogen	69.45 % 16.6 grams	55.23 % 22.9 grams	22.2 % 28.6 grams	17.37 % 11.04 grams
Methane	43.6 % 10.4 grams	27.36 % 11.3 grams	5.98 % 7.7 grams	9.42 % 5.83 grams
Ethylene	57.27 % 13.7 grams	43.76 % 18.1 grams	8.55 % 11 grams	17.43 % 10.94 grams
Carbon Monoxide	52.35 % 12.5 grams	37.62 % 15.6 grams	.264 % .34 grams	15.67 % 9.78 grams
Battery Gases	53.9 % 12.9 grams	39.89 % 16.5 grams	6.98 % 9 grams	13.45 % 8.39 grams
Battery Gases 25k feet	55.35 % 13.3 grams	41.2 % 17.1 grams	n/a	n/a

Simulation results, phi = 1	**Nitrogen**	**Carbon Dioxide**	**Halon 1301**	**2-BTP/CO_2 Mix**
Hydrogen	0.43 cm/sec	.44 cm/sec	1.15 cm/sec	2.64 cm/sec
Methane	3.10 cm/sec	3.42 cm/sec	2.26 cm/sec	2.69 cm/sec
Ethylene	2.57 cm/sec	2.14 cm/sec	1.79 cm/sec	1.19 cm/sec
Carbon Monoxide	.008 cm/sec	0.0113 cm/sec	.34 cm/sec	.27 cm/sec
Battery Gases	1.46 cm/sec	1.27 cm/sec	1.55 cm/sec	1.14 cm/sec
Battery Gases 25k feet	2.20 cm/sec	1.94 cm/sec	n/a	n/a

Flame speeds corresponding to experimental results

Simulation results, phi = 1	**Nitrogen**	**Carbon Dioxide**	**Halon 1301**	**2-BTP/CO_2 Mix**
Hydrogen	1028.2 K	1104.1 K	1582.0 K	1700.4 K
Methane	1557.0 K	1660.0 K	2079.0 K	1912.2 K
Ethylene	1408.9 K	1443.0 K	2020.0 K	1774.4 K
Carbon Monoxide	1521.2 K	1588.4 K	2136.4 K	1739.1 K
Battery Gases	1347.5 K	1392.2 K	2021.5 K	1738.7 K
Battery Gases 25k feet altitude	1316.4 K	1364.7 K	n/a	n/a

Flame temperature corresponding to experimental results

Experimental Results, phi=.8

Experimental results, phi = .8	Nitrogen Required	Carbon Dioxide Required	Halon 1301 Required	2-BTP/CO_2 Required
Hydrogen	70.78 % 16.95 grams	56.67 % 23.5 grams	25.13 % 32.35 grams	19.62 % 12.35 grams
Methane	37.65 % 9.02 grams	24.92 % 10.33 grams	3.98 % 5.12 grams	11.39 % 7.16 grams
Ethylene	49.49 % 11.85 grams	35.83 % 14.86 grams	4.78 % 6.15 grams	19.37 % 12.28 grams
Carbon Monoxide	45.56 % 10.9 grams	31.69 % 13.14 grams	0.24 % 0.31 grams	12.08 % 7.57 grams
Battery Gases	49.77 % 11.92 grams	36.63 % 15.19 grams	6.06 % 7.8 grams	16.67 % 10.41 grams

Simulation results, phi = .8	Nitrogen	Carbon Dioxide	Halon 1301	2-BTP/CO_2 Mix
Hydrogen	.0074 cm/sec	0.019 cm/sec	0.68 cm/sec	1.82 cm/sec
Methane	3.37 cm/sec	3.12 cm/sec	1.98 cm/sec	2.39 cm/sec
Ethylene	3.57 cm/sec	3.37 cm/sec	2.94 cm/sec	0.94 cm/sec
Carbon Monoxide	0.0108 cm/sec	0.0143 cm/sec	0.29 cm/sec	0.61 cm/sec
Battery Gases	1.46 cm/sec	1.3 cm/sec	0.9913 cm/sec	0.83 cm/sec

Flame speeds corresponding to experimental results

Simulation results, phi = .8	Nitrogen	Carbon Dioxide	Halon 1301	2-BTP/CO_2 Mix
Hydrogen	895.5 K	969.8 K	1510.2 K	1707.9 K
Methane	1450.2 K	1494.3 K	1938.1 K	1975.9 K
Ethylene	1369.9 K	1410.2 K	2085.2 K	1798.3 K
Carbon Monoxide	1491.0 K	1544.3 K	2030.7 K	2002.4 K
Battery Gases	1262.4 K	1292.7 K	1839.5 K	1747.7 K

Flame temperature corresponding to experimental results

Experimental Results, phi=.6

- Since required 2-BTP/CO_2 agent concentration increased from phi=1 to phi=.8, an additional test series was performed at phi=.6 to see if required agent continued to increase.

Experimental results, phi = .6	Nitrogen	Carbon Dioxide	Halon 1301	2-BTP/CO_2 Mix Required
Methane	n/a	n/a	n/a	6.79 % 4.23 grams

- 2-BTP/CO_2 required:
  - phi=1: 9.42 liters
  - phi=.8: 11.39 liters
  - phi=.6: 6.79 liters

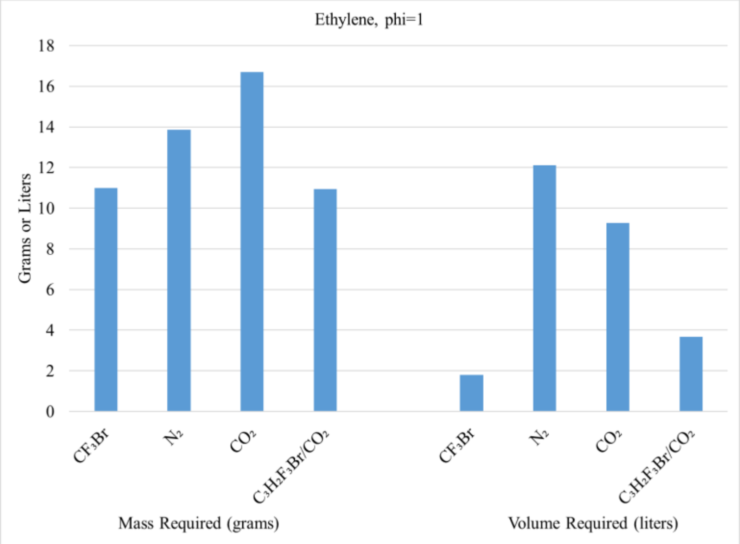
Comparison of results phi=1 vs. phi=.8

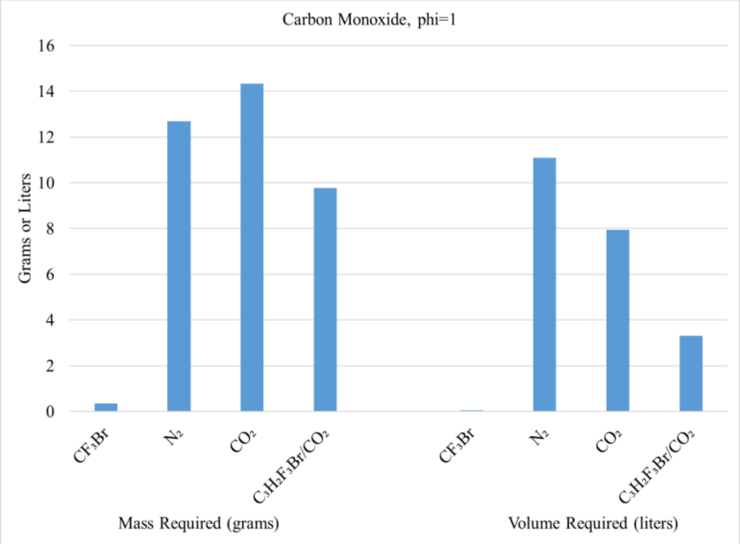
Experimental results, phi = 1	Nitrogen Required	Carbon Dioxide Required	Halon 1301 Required	2-BTP/CO_2 Mix Required
Hydrogen	69.45 % 16.6 grams	55.23 % 22.9 grams	22.2 % 28.6 grams	17.37 % 11.04 grams
Methane	43.6 % 10.4 grams	27.36 % 11.3 grams	5.98 % 7.7 grams	9.42 % 5.83 grams
Ethylene	57.27 % 13.7 grams	43.76 % 18.1 grams	8.55 % 11 grams	17.43 % 10.94 grams
Carbon Monoxide	52.35 % 12.5 grams	37.62 % 15.6 grams	.264 % .34 grams	15.67 % 9.78 grams
Battery Gases	53.9 % 12.9 grams	39.89 % 16.5 grams	6.98 % 9 grams	13.45 % 8.39 grams
Battery Gases 25k feet	55.35 % 13.3 grams	41.2 % 17.1 grams	n/a	n/a

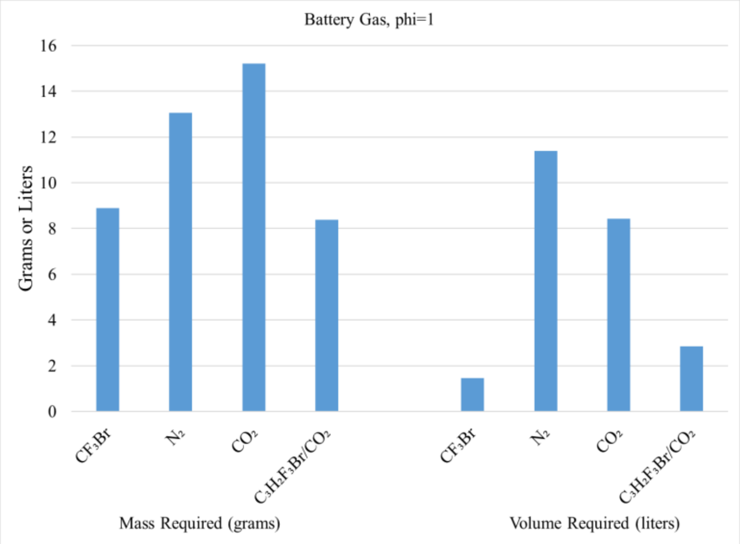
Experimental results, phi = .8	Nitrogen Required	Carbon Dioxide Required	Halon 1301 Required	2-BTP/CO_2 Required
Hydrogen	70.78 % 16.95 grams	56.67 % 23.5 grams	25.13 % 32.35 grams	19.62 % 12.35 grams
Methane	37.65 % 9.02 grams	24.92 % 10.33 grams	3.98 % 5.12 grams	11.39 % 7.16 grams
Ethylene	49.49 % 11.85 grams	35.83 % 14.86 grams	4.78 % 6.15 grams	19.37 % 12.28 grams
Carbon Monoxide	45.56 % 10.9 grams	31.69 % 13.14 grams	0.24 % 0.31 grams	12.08 % 7.57 grams
Battery Gases	49.77 % 11.92 grams	36.63 % 15.19 grams	6.06 % 7.8 grams	16.67 % 10.41 grams

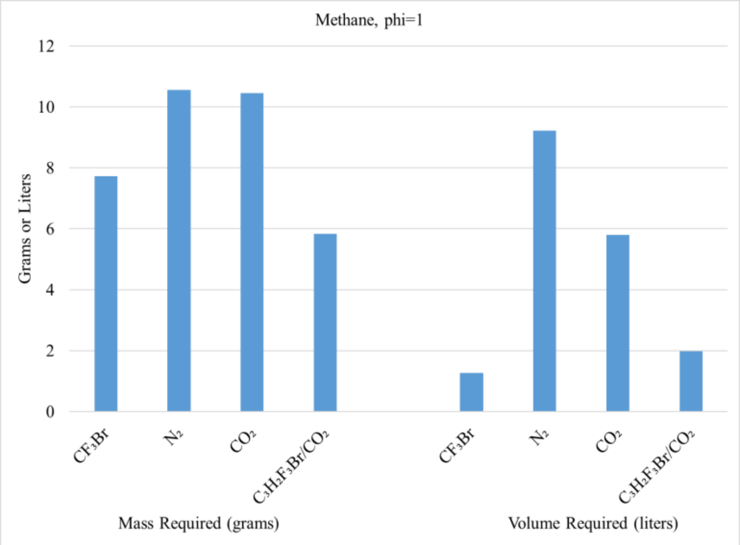
- For most mixture, a greater concentration of agent was required at phi=1 vs. phi=.8, except:
  - Hydrogen and Nitrogen
  - Hydrogen and Carbon Dioxide
  - Hydrogen and Halon 1301
  - Hydrogen and 2-BTP/CO_2
  - Methane and 2-BTP/CO_2
  - Ethylene and 2-BTP/CO_2
  - Battery gas and 2-BTP/CO_2

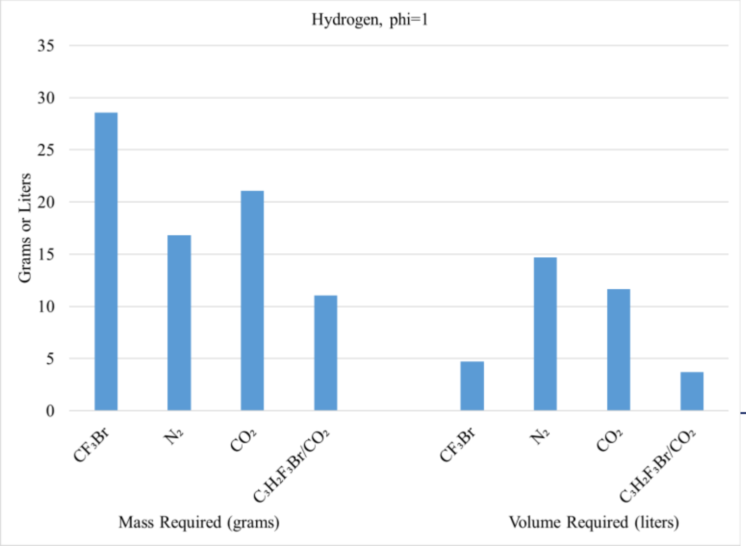
Mass required vs. volume required





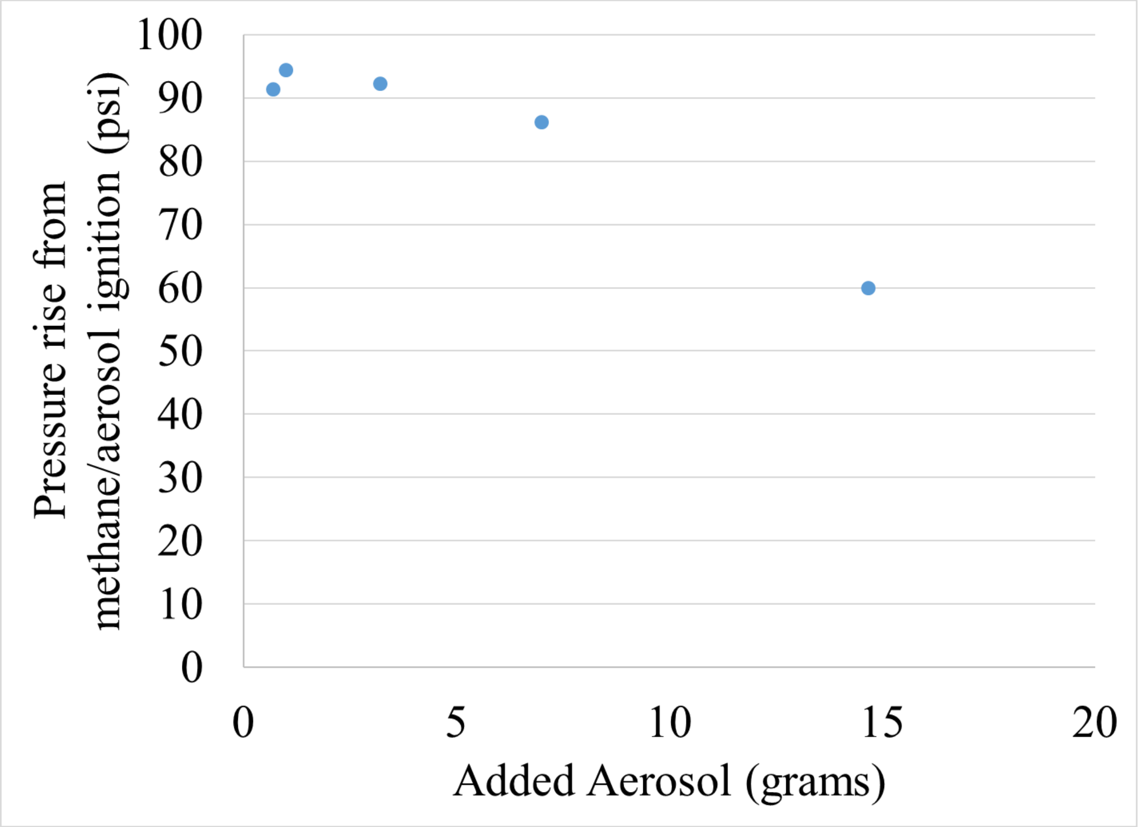






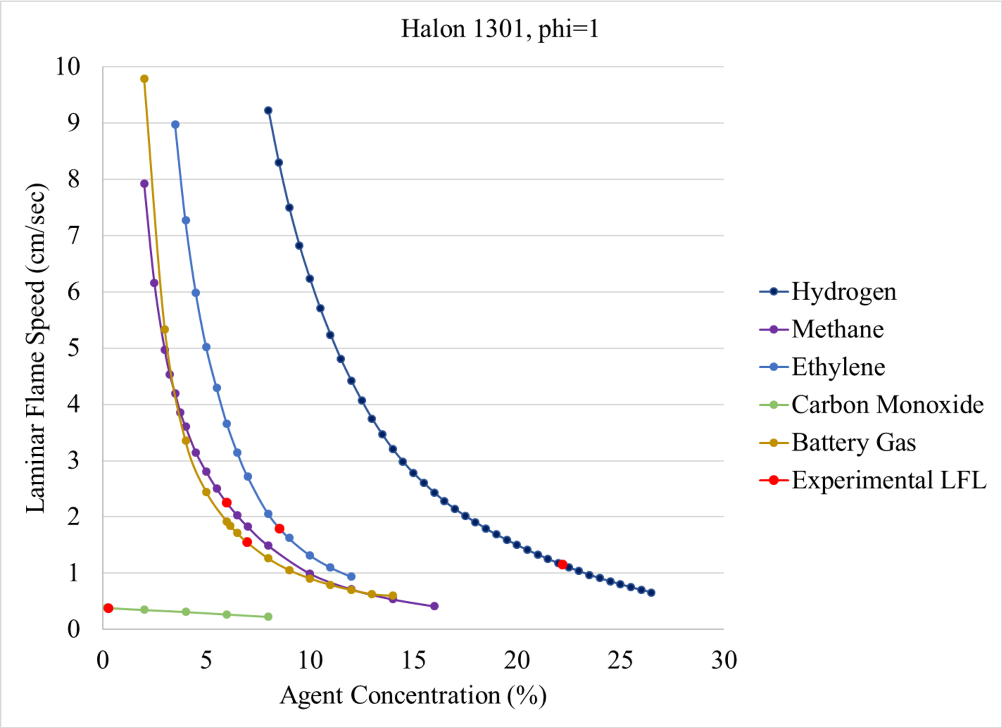
- CF_3Br was most effective against CO and least effective against H_2
- In most cases, N_2 was more effective than CO_2 by volume but less effective by mass.
- In most cases, 2-BTP/CO_2 was more effective than CF_3Br by volume but similarly effective by mass.
- In most cases, CF_3Br and 2-BTP/CO_2 were more effective than N_2 and CO_2

Aerosol Results

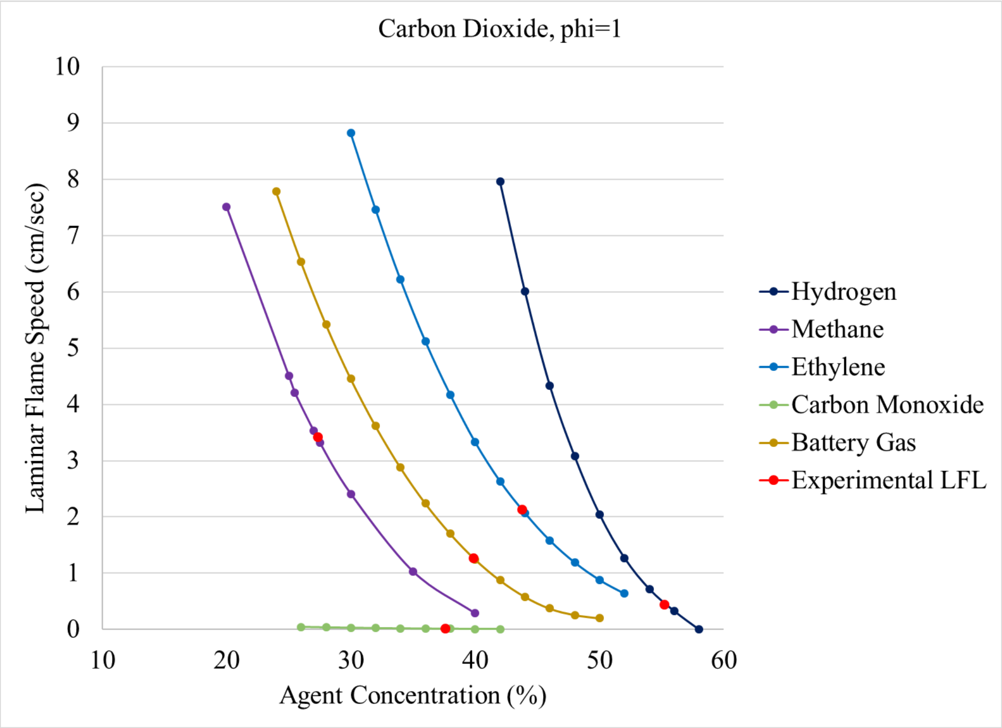


- Aerosol was fairly ineffective when ducted into the vessel from an external chamber
- When the aerosol was ignited within the vessel, and tested with methane at phi=1, 5 grams was effective and 2.2 grams was not effective.

Halon and CO_2, Laminar Flame Speed

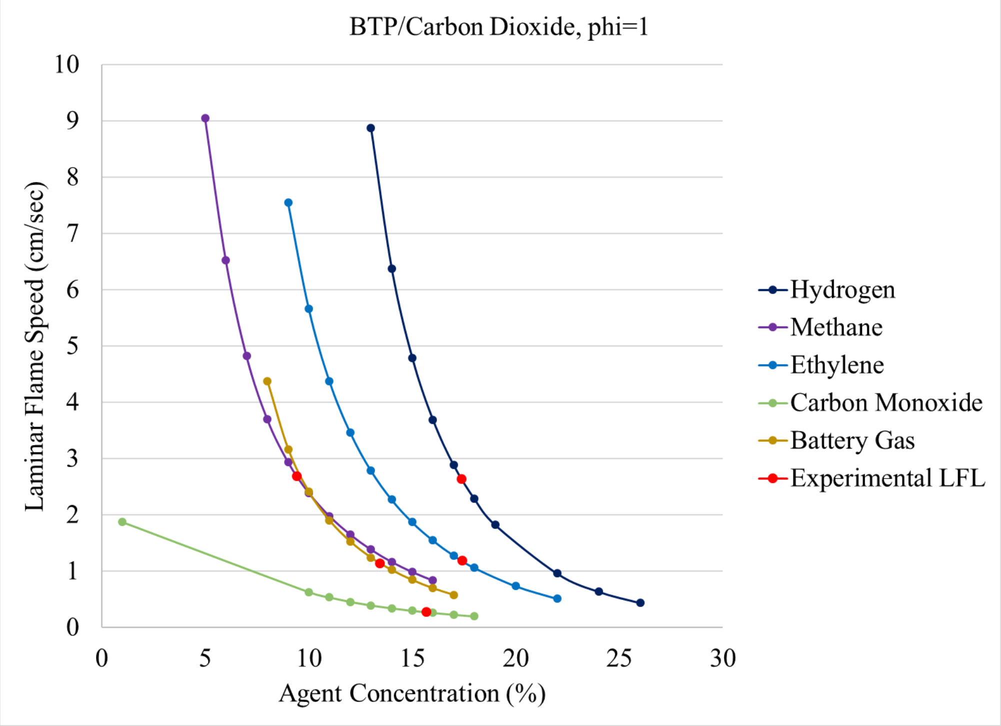


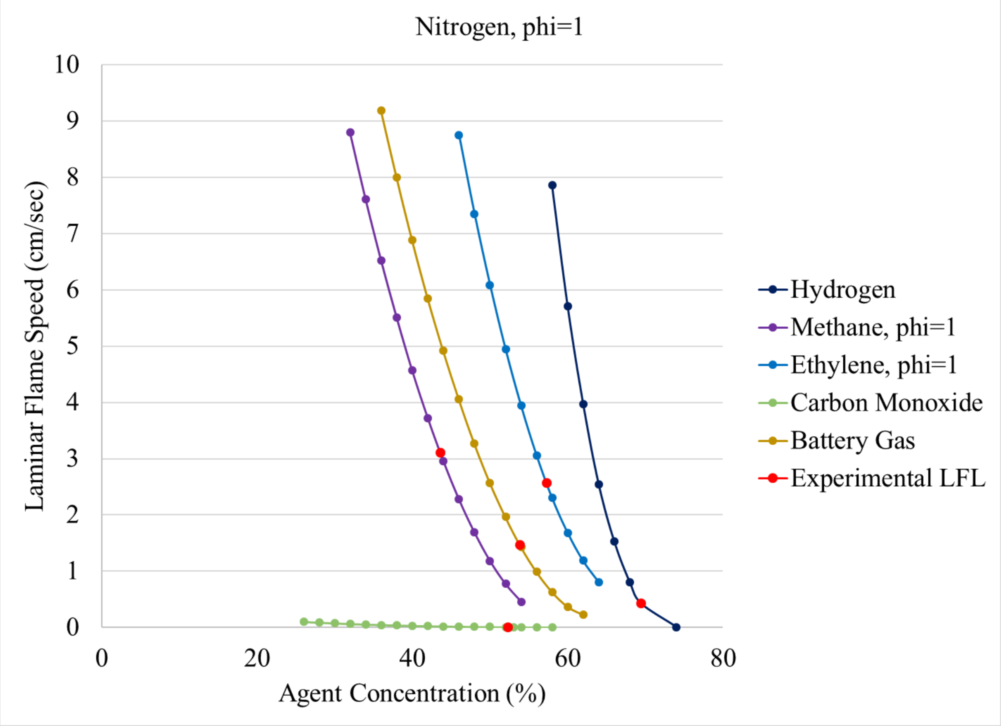
- Inerting laminar flame speeds occur between 1.5cm/sec and 3.5cm/sec for all flammable gases except carbon monoxide.



- Inerting laminar flame speeds occur between .4 cm/sec and 3.4cm/sec for all flammable gases except carbon monoxide.

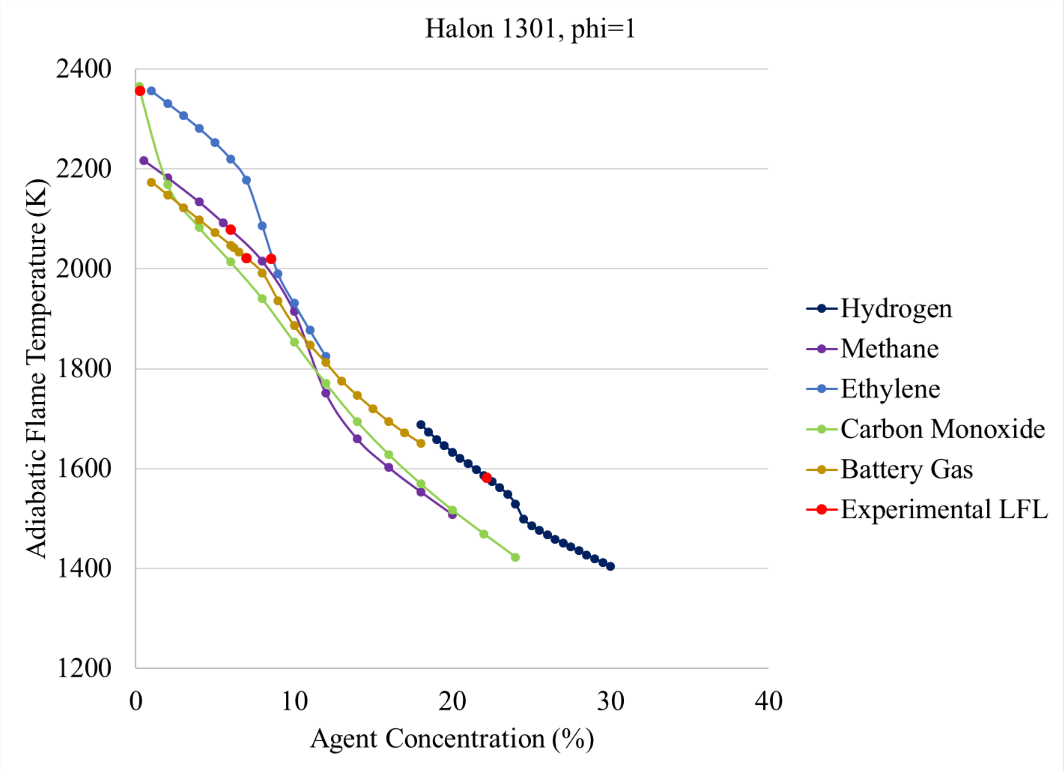
2-BTP and N_2, Laminar Flame Speed

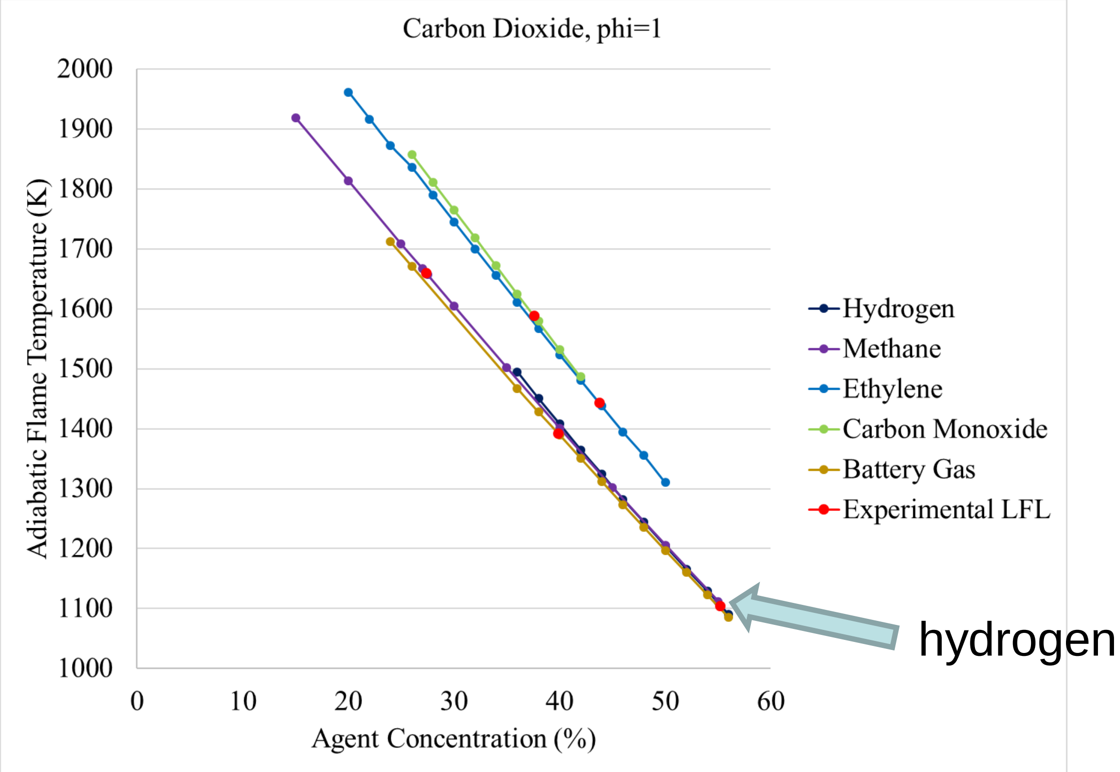




- Inerting laminar flame speeds occur between 1.1cm/sec and 2.7cm/sec for all flammable gases except carbon monoxide.
- Inerting laminar flame speeds occur between .4 cm/sec and 3.1cm/sec for all flammable gases except carbon monoxide.

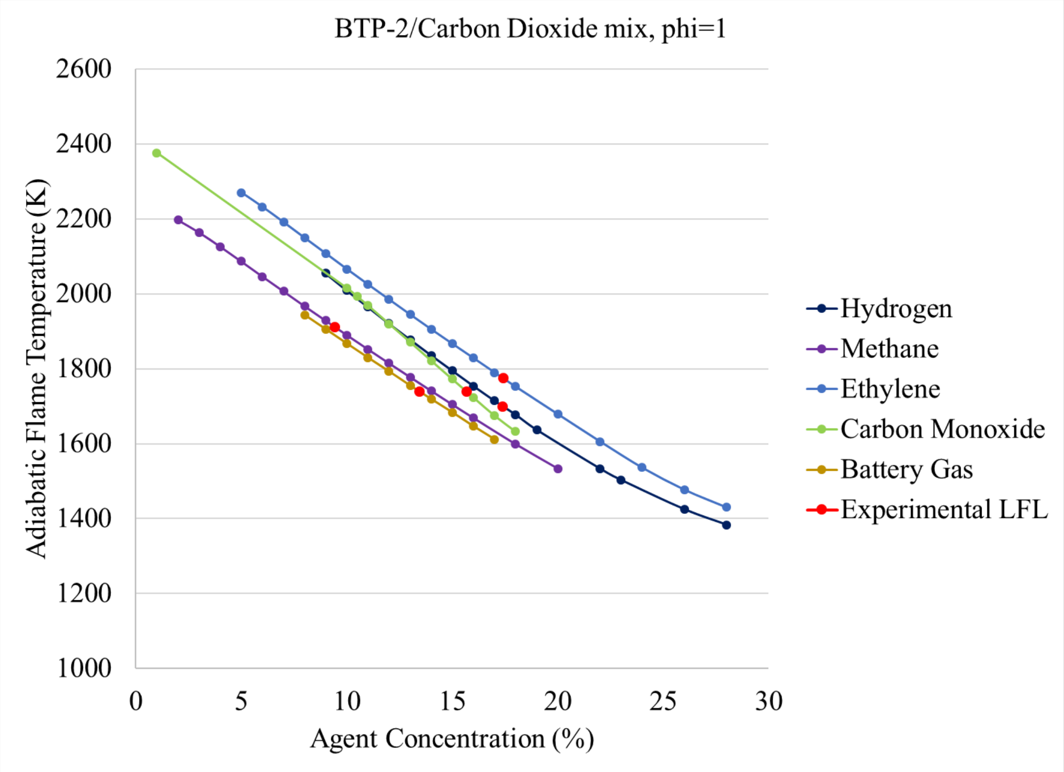
Halon and CO_2, Adiabatic Flame Temperature

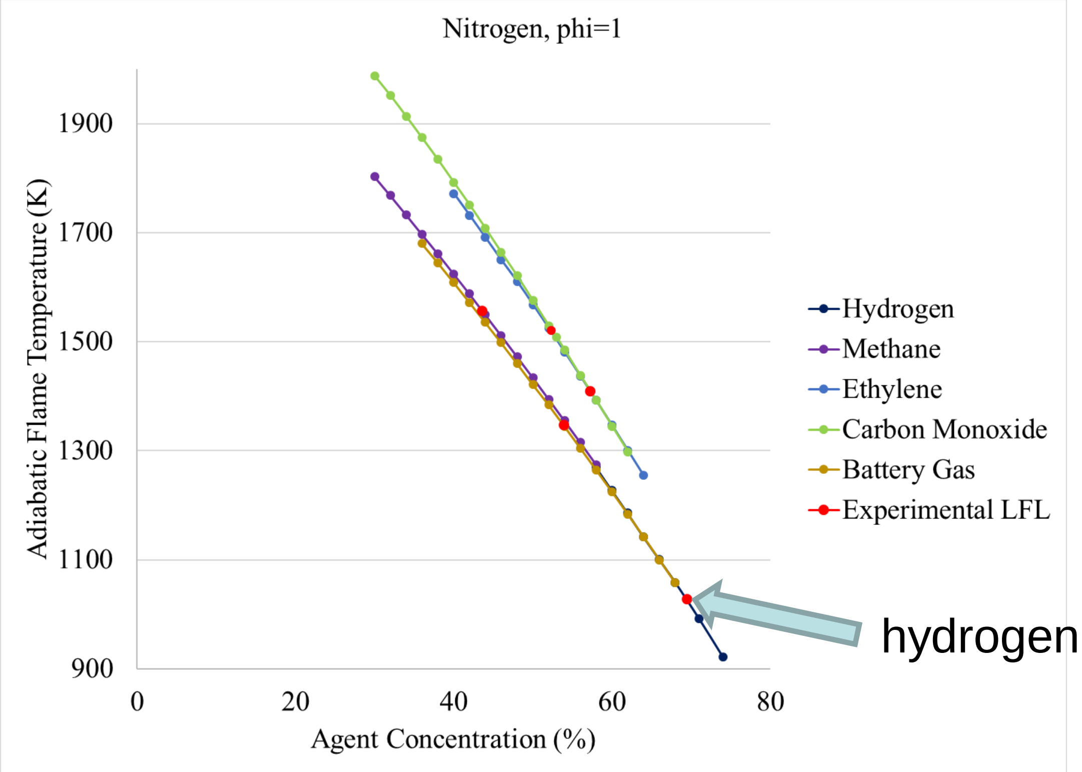




- Inerting adiabatic flame temperatures occur between 2000K and 2400K for all flammable gases except hydrogen.
- Inerting adiabatic flame temperatures occur between 1400K and 1660K for all flammable gases except hydrogen.

2-BTP/CO_2 and N_2, Adiabatic Flame Temperature





- Inerting adiabatic flame temperatures occur between 2000K and 2400K for all flammable gases except hydrogen.
- Inerting adiabatic flame temperatures occur between 1400K and 1660K for all flammable gases except hydrogen.

Prediction of agent effectiveness at elevated temperature (200C)

Simulation results, phi = 1	Nitrogen	Carbon Dioxide	Halon 1301	2-BTP/CO_2 Mix
Hydrogen	78.02 %	64.32 %	32.49 %	23.38 %
Methane	55.68 %	37.4 %	10.8 %	15.6 %
Ethylene	67.8 %	54.4 %	14.34 %	23.93 %
Carbon Monoxide	62.92 %	47.82 %	n/a	24.02 %
Battery Gases	64.76 %	49.95 %	13.87 %	20.16 %

Predictions of inerting concentrations based on the flame speed that corresponded to experimentally found inerting concentrations at sea level pressure

Simulation results, phi = 1	Nitrogen	Carbon Dioxide	Halon 1301	2-BTP/CO_2 Mix
Hydrogen	76.05 %	62.35 %	24.56 %	20.9 %
Methane	50.896 %	33.257 %	8.98 %	12.65 %
Ethylene	63.6 %	49.732 %	10 %	20.74 %
Carbon Monoxide	58.68 %	43.17 %	3.85 %	18.33 %
Battery Gases	61.23 %	46.53 %	9.24 %	17 %

Predictions of inerting concentrations based on the flame temperature that corresponded to experimentally found inerting concentrations at sea level pressure

- Flame speeds predicted higher concentrations than flame temperatures
- A much greater quantity of fire extinguishing agent will be required for elevated temperature conditions.

Prediction of agent effectiveness at reduced pressure (25000 feet)

Simulation results, phi = 1	Nitrogen	Carbon Dioxide	Halon 1301	2-BTP/CO_2 Mix
Hydrogen	n/a	n/a	22.5 %	18.21 %
Methane	49.47 %	32.67 %	6.69 %	10.48 %
Ethylene	60.34 %	46.69 %	8.92 %	18.26 %
Carbon Monoxide	52.36 %	37.60 %	n/a	n/a
Battery Gases	57.90 %	44.03 %	n/a	14.39 %

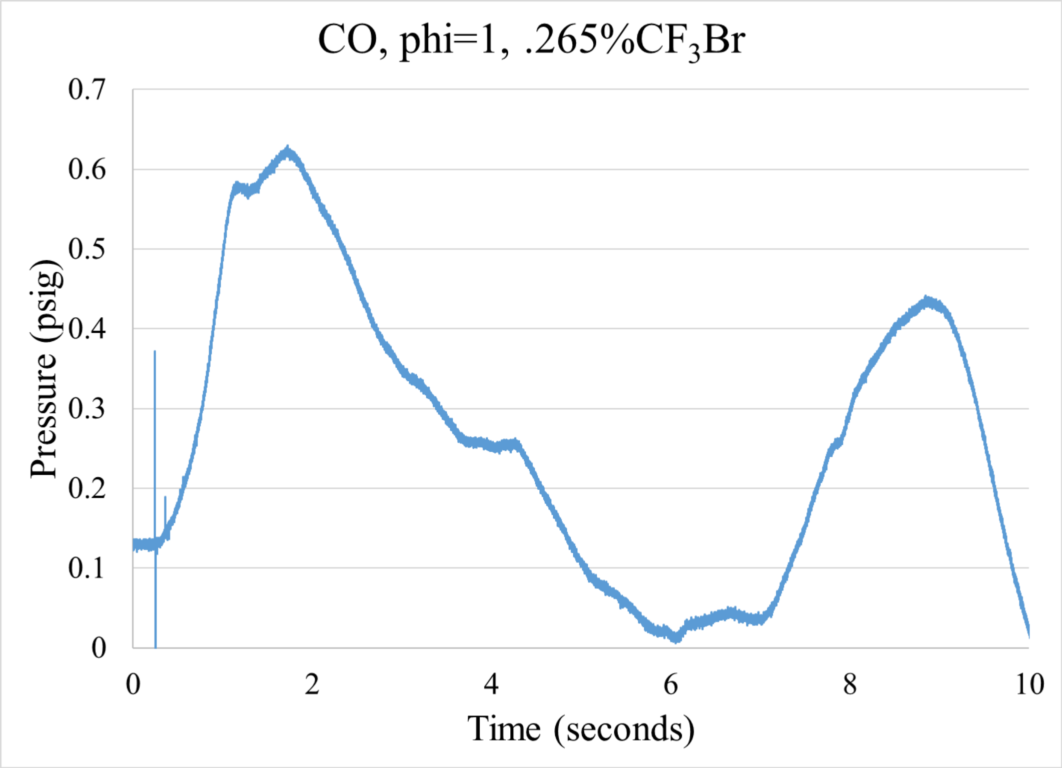
Predictions of inerting concentrations based on the flame speed that corresponded to experimentally found inerting concentrations at sea level pressure

Simulation results, phi = 1	Nitrogen	Carbon Dioxide	Halon 1301	2-BTP/CO_2 Mix
Hydrogen	68.87 %	n/a	21.09 %	18.21 %
Methane	n/a	26.90 %	5.26 %	9.28 %
Ethylene	57.09 %	43.28 %	8.6 %	17.24 %
Carbon Monoxide	52.36 %	37.53 %	n/a	n/a
Battery Gases	53.77%	39.62 %	n/a	13.3 %

Predictions of inerting concentrations based on the flame temperature that corresponded to experimentally found inerting concentrations at sea level pressure

- Flame speeds again predicted higher concentrations than flame temperatures
- There was little difference between predicted required inerting concentrations at altitude vs. sea level pressure if anything, predictions showed that slightly more agent would be required at altitude.
  - Consistent with experimental results with battery gas/N_2 and battery gas/CO_2

Miscellaneous effects



- Some mixtures had long, drawn-out flame fronts that stayed just below flammability criterion
  - Halon and CO (shown above)
  - Halon and Ethylene

Summary of Results

- Halon 1301 is extremely effective at suppressing CO ignition
- Halon 1301 is significantly less effective at suppressing H_2 ignition than it is with other flammable gases.
- N_2 and CO_2 are slightly more effective at sea level pressure against lithium battery gas ignition than at altitude.
- Halon 1301 can experience slight overpressure with certain quantities of Hydrogen. Rate-of-pressure-rise, however, was significantly reduced for all concentrations.
- Flame speed and adiabatic flame temperature found from simulations were shown to be a reasonable predictor of flammability.
- Nitrogen and carbon dioxide were slightly more effective against lithium battery gases at sea level pressure than at altitude. Simulations were conducted to predict required inerting concentrations for other agents and flammable gases and similar results were found. The difference was minimal between altitude and sea level pressure.

Summary of Results (continued)

- **Hydrogen inerting occurs at a relatively low adiabatic flame temperature**
- **CO inerting occurs at a relatively high adiabatic flame temperature**
- **The greatest amount of extinguishing agent was required for all flammable gases at about phi=1 except Hydrogen. For Hydrogen, the greatest amount of agent was required for relatively lean mixtures.**
- **Halon 1301 is significantly more effective than Blend-D against CO (by volume and mass)**
- **Blend-D ($C_3H_2F_3Br$, CO_2 mix) is more effective than Halon 1301 against H_2 (by volume and mass)**
- **Halon 1301 (CF_3Br) is more effective than Blend-D against CH_4 (by volume, not mass)**
- **Halon and Blend-D**
  - Halon 1301 is more effective than Blend-D against C_2H_4 (by volume, not mass) at phi=1
  - Halon 1301 is twice as effective as Blend-D against C_2H_4 by mass at phi=.8

Application to Industry

- It may be necessary in the future to develop additional extinguishing agent requirements to demonstrate that they are suitable for safe shipment of lithium batteries on aircraft.
- 17% more CO_2 than N_2 by mass is required for battery gas inertion but, 35% more N_2 than CO_2 by volume is required for battery gas inertion. Results of this study can inform future designs and tradeoffs between mass and volume requirements.
- Elevated cargo compartment temperatures would require significantly higher agent concentrations. Current aircraft cargo compartment requirements do not account for elevated temperatures.

Questions?