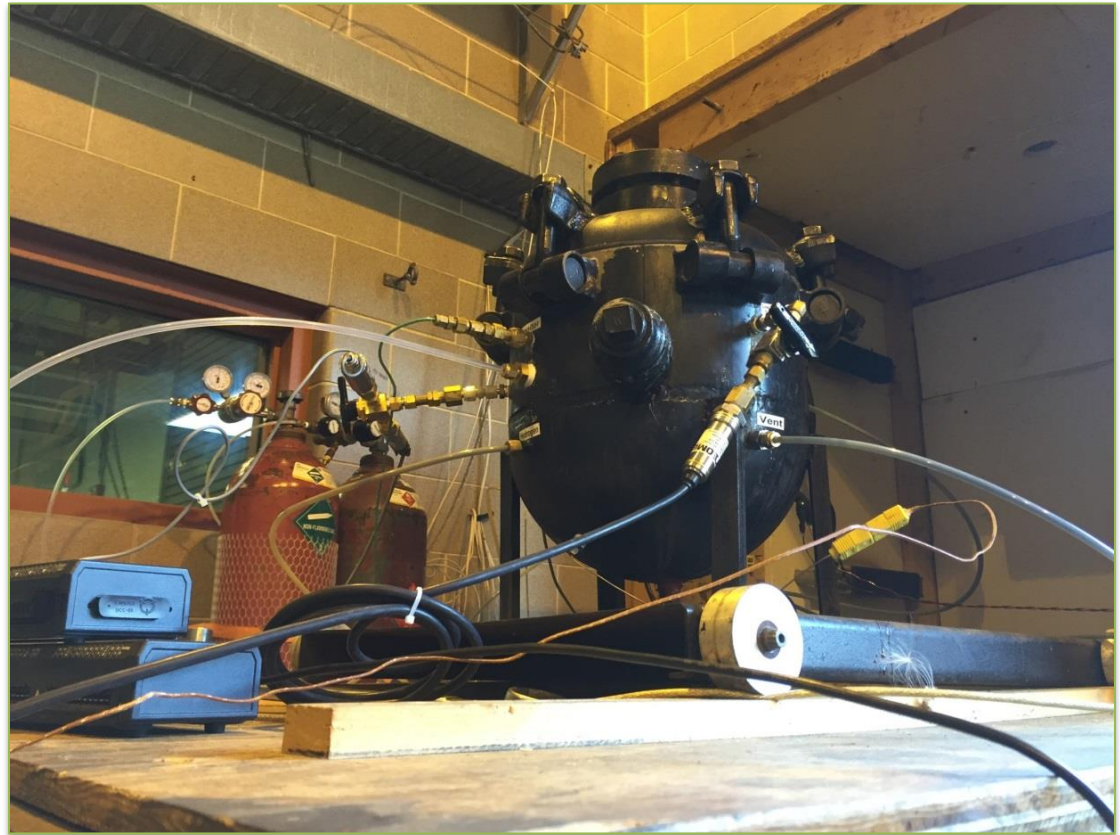


FLAMMABILITY LIMITS OF LITHIUM BATTERY THERMAL RUNAWAY VENT GAS IN AIR AND THE INERTING EFFECTS OF HALON 1301

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FAA



1

Introduction

1.1 Relevant Definitions

1.2 Topic Background

1.3 Aviation Regulations

1.4 Scope of Study

1.5 Test Equipment

1.6 Test Procedure

Definitions

- **Lower Flammability Limit (LFL)** is the minimum concentration of a fuel in an oxidizer that will ignite. *Less fuel will be too lean to ignite.*
- **Upper Flammability limit (UFL)** is the maximum concentration of a fuel in an oxidizer that will ignite. *More fuel will be too rich to ignite.*
- **Minimum Inerting Concentration (MIC)** is the minimum concentration of an inertant required to prevent ignition regardless of fuel concentration.
 - This is also where the LFL meets the UFL

Background

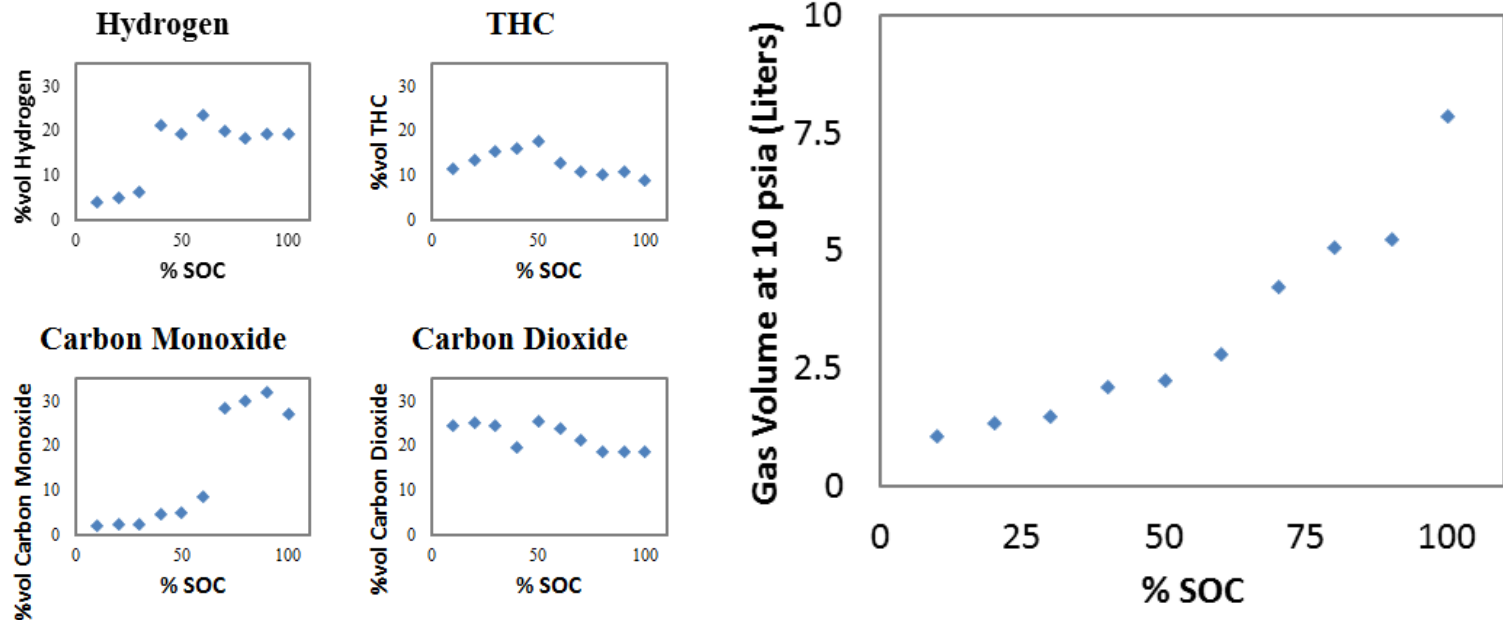
- This table shows variables and its effect on the flammability limits

An increase in the variable...	Causes the flammability limits to...
Spark Energy [1]	Expand
Ambient Temperature [1]	Expand
Ambient Pressure [2]	Constrict
Pressure Vessel Volume [3]	Constrict

The application of flammability limits should be applied carefully while considering all possible variables. The above variables have been shown to effect data outcome.

Background

- Testing was conducted to determine the constituents of 18650-sized LiCoO_2 rechargeable lithium-ion battery cell vent gases at various states of charge [4].
- The three main constituents were found to be carbon monoxide (CO), carbon dioxide (CO_2), and hydrogen (H_2) [4]. The remaining constituents are various hydrocarbons [4].
- It was found that increasing the SOC increases the overall lithium battery vent gas volume and changes the lithium battery vent gas composition [4].



These tests were used to confirm the chemical makeup of the premixed lithium-ion battery vent gas (*Li-Ion pBVG*) used for testing.

Background

- Lithium batteries are commonly used and can be packed in bulk and shipped in the cargo holds of freighter aircraft
- Currently lithium batteries are banned from bulk shipment on passenger aircraft [5].
- A lithium battery in thermal runaway can propagate from cell to cell and box to box [6]
 - 1668 degrees F in lithium-ion cells (rechargeable) [6]
 - 2009 degrees F in lithium metal cells (non-rechargeable) [6]



Regulations

- Class C cargo compartment utilizes [7]
 - Fire resistant liner
 - Early fire detection
 - An isolated and built in fire extinguishing system
 - 5 %vol Halon 1301 knockdown concentration
 - 3 %vol Halon 1301 sustained for remaining duration of flight

* Title 14 Code of Federal Regulations (CRF) part 25 §25.857

- ***But is that sufficient for lithium-ion battery fires?***
 - The objective of this work is to determine if the 5 %vol knockdown and the 3 %vol sustained of Halon 1301 in a Class C cargo compartment are sufficient to render the buildup of a lithium-ion battery vent gas (Li-Ion BVG) in air inert.

Scope

- Experimentally determine the LFL and UFL of hydrogen and air mixtures
- Experimentally determine the inerting effects of Halon 1301 on hydrogen and air mixtures
 - LFL and UFL with 10 %vol Halon 1301
 - LFL and UFL with 20 %vol Halon 1301
 - MIC of Halon 1301 on hydrogen and air mixtures

Scope

- Experimentally determine the LFL and UFL of *Li-Ion pBVG* and air mixtures
- Experimentally determine the inerting effects of Halon 1301 on *Li-Ion pBVG* and air mixtures
 - LFL and UFL with 5 %vol Halon 1301
 - LFL and UFL with 7 %vol Halon 1301
 - LFL and UFL with 8 %vol Halon 1301
 - MIC of Halon 1301 on Li-Ion pBVG and air mixtures

Scope

- Compare experimental results to calculated results using *Le Chatelier's mixing rule* for determining the flammability limits of lithium battery vent gas in air.
- Predict flammability limits for various states of charge using *Le Chatelier's mixing rule*.

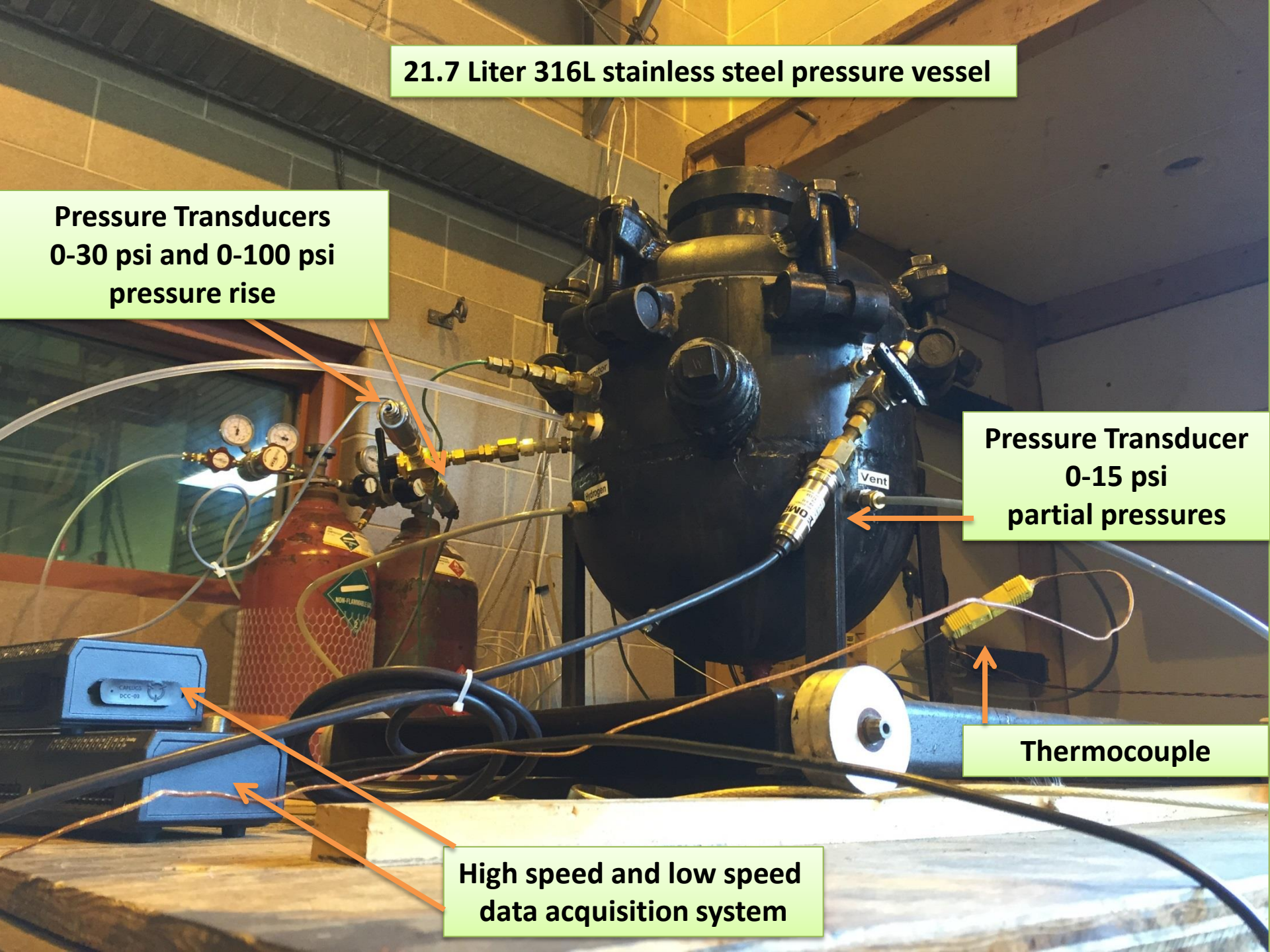
21.7 Liter 316L stainless steel pressure vessel

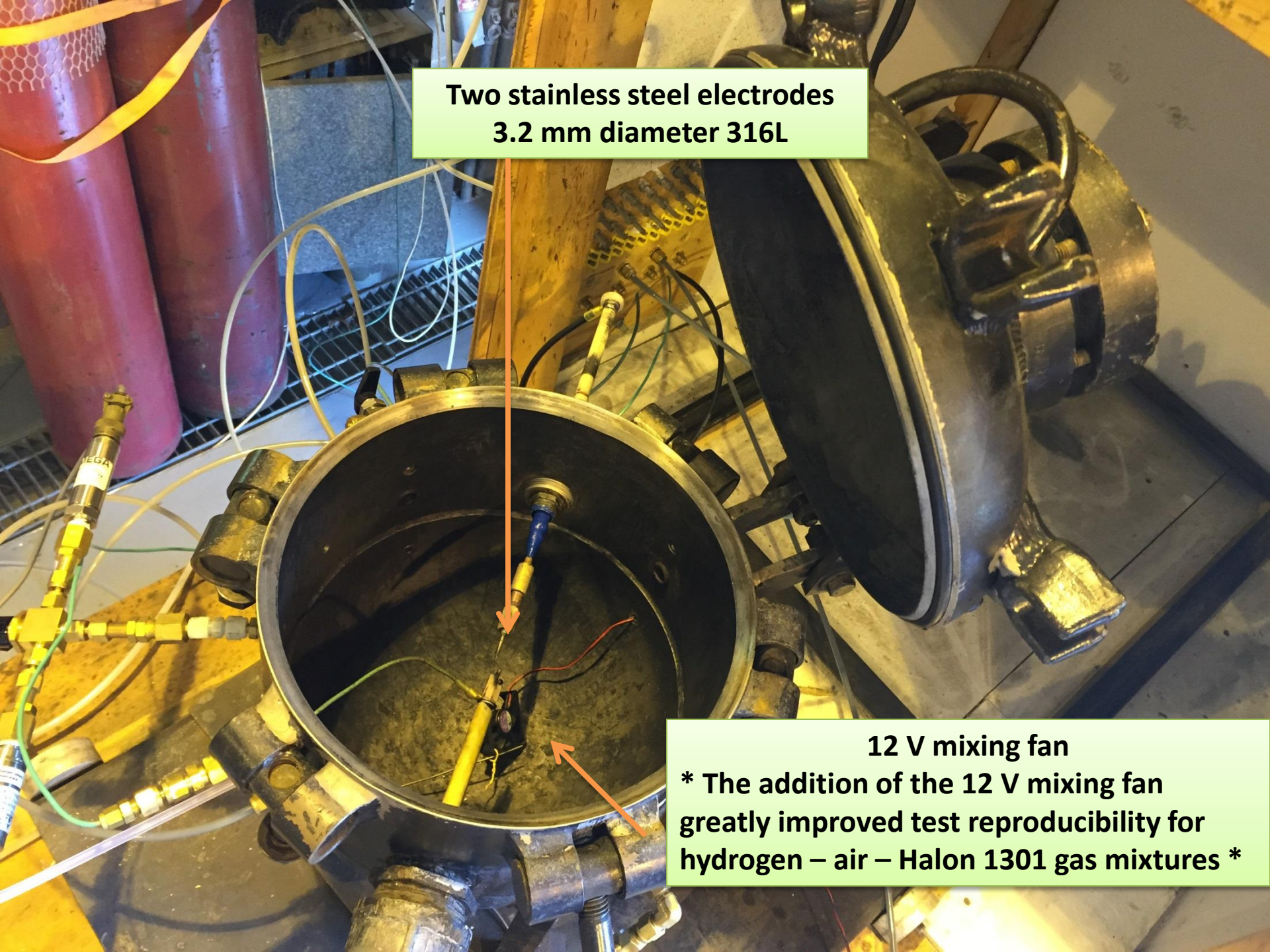
**Pressure Transducers
0-30 psi and 0-100 psi
pressure rise**

**Pressure Transducer
0-15 psi
partial pressures**

Thermocouple

**High speed and low speed
data acquisition system**



A photograph of a stainless steel test chamber, likely a bomb calorimeter, with its lid removed. Two stainless steel electrodes are visible inside, one of which is pointed to by a red arrow. A 12V mixing fan is also visible inside, pointed to by another red arrow. The chamber is surrounded by various cables and equipment, including a red gas cylinder on the left. The background shows a laboratory setting with wooden beams and a metal grate.

**Two stainless steel electrodes
3.2 mm diameter 316L**

12 V mixing fan
*** The addition of the 12 V mixing fan
greatly improved test reproducibility for
hydrogen – air – Halon 1301 gas mixtures ***

2

Test Procedures

2.1 Testing Equipment

2.2 Testing Procedure

2.3 Test Criterion

2.4 Test Example

2.5 Determining Limits

Testing Equipment

Components *not* described in the previous slides are:

- 15 kV, 30mA luminous tube transformer
 - To generate spark energy
- Needle valves
 - To accurately insert gases into testing vessel
- Vacuum Pump
 - To void the testing vessel of initial gases

Testing Equipment

- The premixed bottled lithium battery vent gas constituents are listed below [4]
- The most prevalent gases are hydrogen, carbon monoxide, and carbon dioxide.

Gas	%vol
Hydrogen	27.60
Carbon Monoxide	22.90
Carbon Dioxide	30.10
Methane	6.37
Propylene	4.48
Ethylene	2.21
Butane	1.57
Ethane	1.17
1-Butane	0.56
Propane	0.27

Rather than collecting Li-Ion battery vent gases, a bottle of premixed battery vent gases (Praxair NI BT1.58X1CASN) was purchased to match the composition of collected battery gases.

Testing Procedure

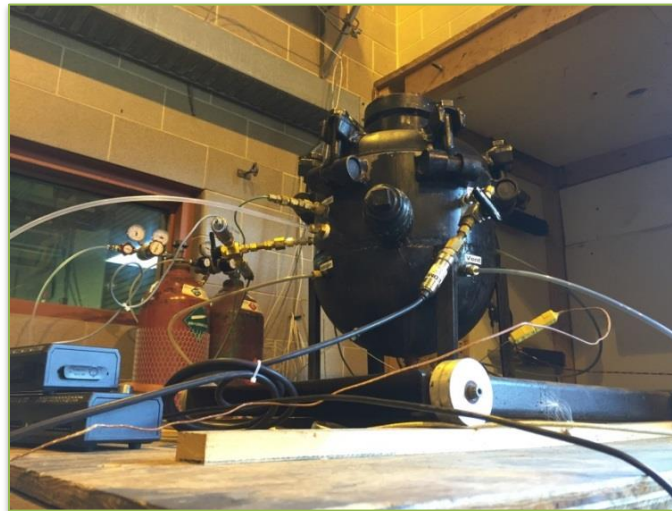
The test procedure from start to finish requires approximately 45 minutes per test. The steps are summarized below:

1. Evacuate test vessel with vacuum to an average of 0.14 psi
2. Use partial pressure to accurately input the required ratio of gases to a total of 14.7 psi
3. Turn on 12 V mixing fan
4. Turn off fan
5. Ignite mixture
6. Measure pressure rise
7. Analyze data
8. Repeat steps 1 through 7



Test Criterion

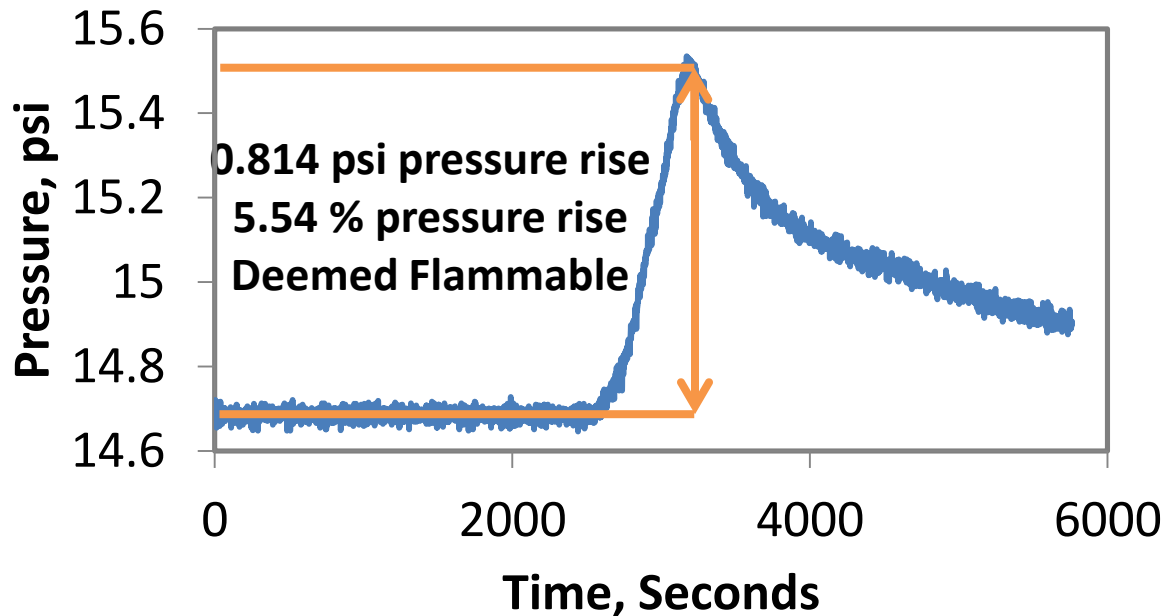
- A flammability limit of 5 % pressure rise over initial pressure is used to consider a mixture flammable
- Five test results are averaged to determine the flammability limits
They are to be:
 - Below the 5 % pressure rise limit
 - Within 0.05 %vol fuel concentration of one another



Test Example

This test started at 14.68 psi and rose to 15.51 psi after ignition. After subtracting 0.016 psi for pressure rise from spark alone, There is a pressure rise of 0.814 psi and a *percent pressure rise of 5.54 %*. This is greater than 5 %, therefore, this particular test is considered flammable.

**20.00 % Halon 1301, 28.065 %
Hydrogen, 51.93 % Air**

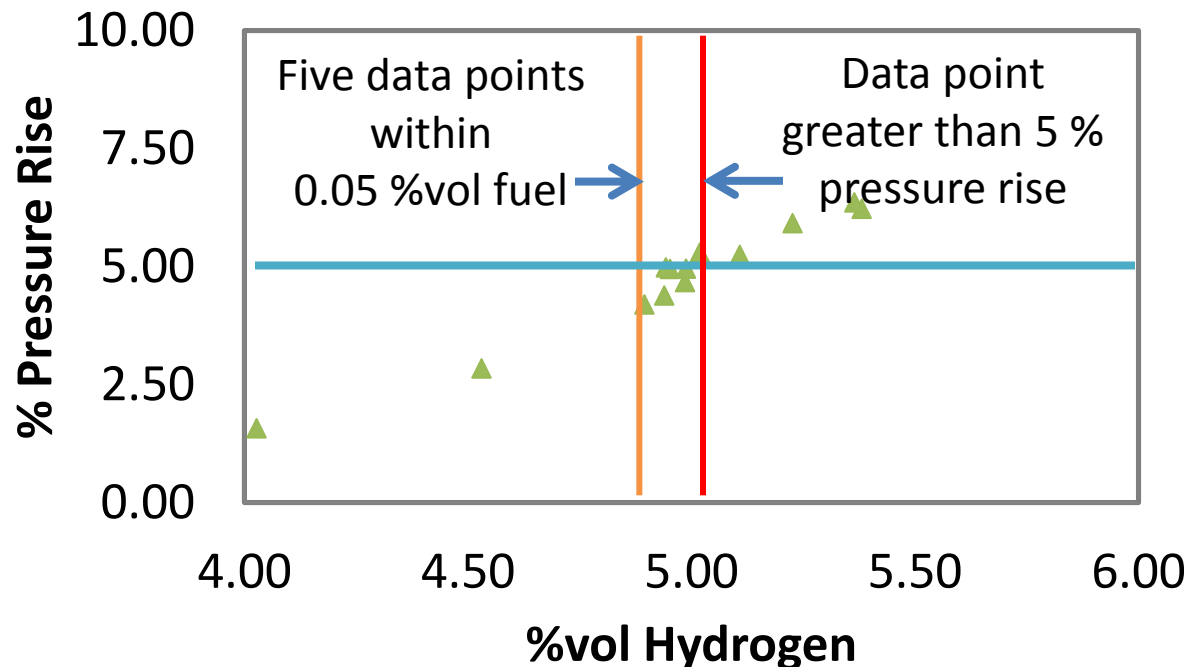


The above graph demonstrates a flammable test result.

Determining LFL

1. Perform test near flammability limit of 5 % pressure rise.
2. Increase or decrease concentration until test is conducted below 5 % pressure rise
3. Conduct four more tests within 0.05 % fuel concentration of one another without exceeding 5 % pressure rise.
4. Repeat steps 1 through 3 if necessary and average five results.

Hydrogen - Air LFL



The above graph demonstrates how the LFL is determined.

3

Flammability Limits and MIC of Hydrogen and Air Mixtures with and without Halon 1301

3.1 Overview

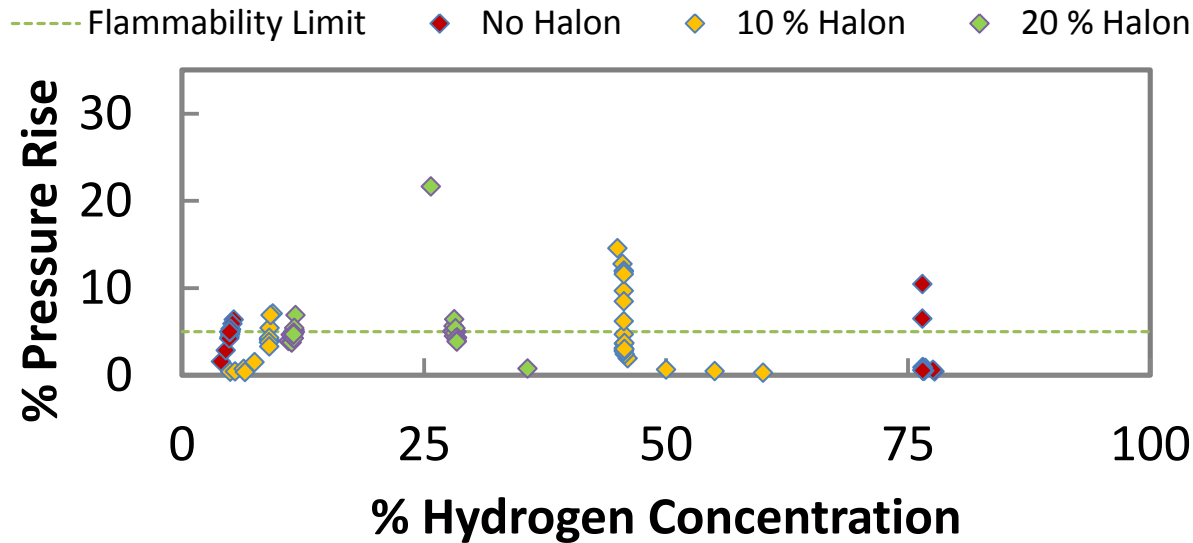
3.2 Nose Cap MIC of Hydrogen, Air, and Halon 1301 Mixtures

3.3 Flammability Curve of Hydrogen, Air, and Halon 1301 Gas
Mixtures

Overview

Mixture	LFL, %vol Hydrogen	UFL, %vol Hydrogen
Hydrogen – Air	4.95±0.40	76.52±0.44
Hydrogen – Air – 10 % Halon 1301	9.02±0.51	45.70±0.41
Hydrogen – Air – 20 % Halon 1301	11.55±0.48	28.39±0.47

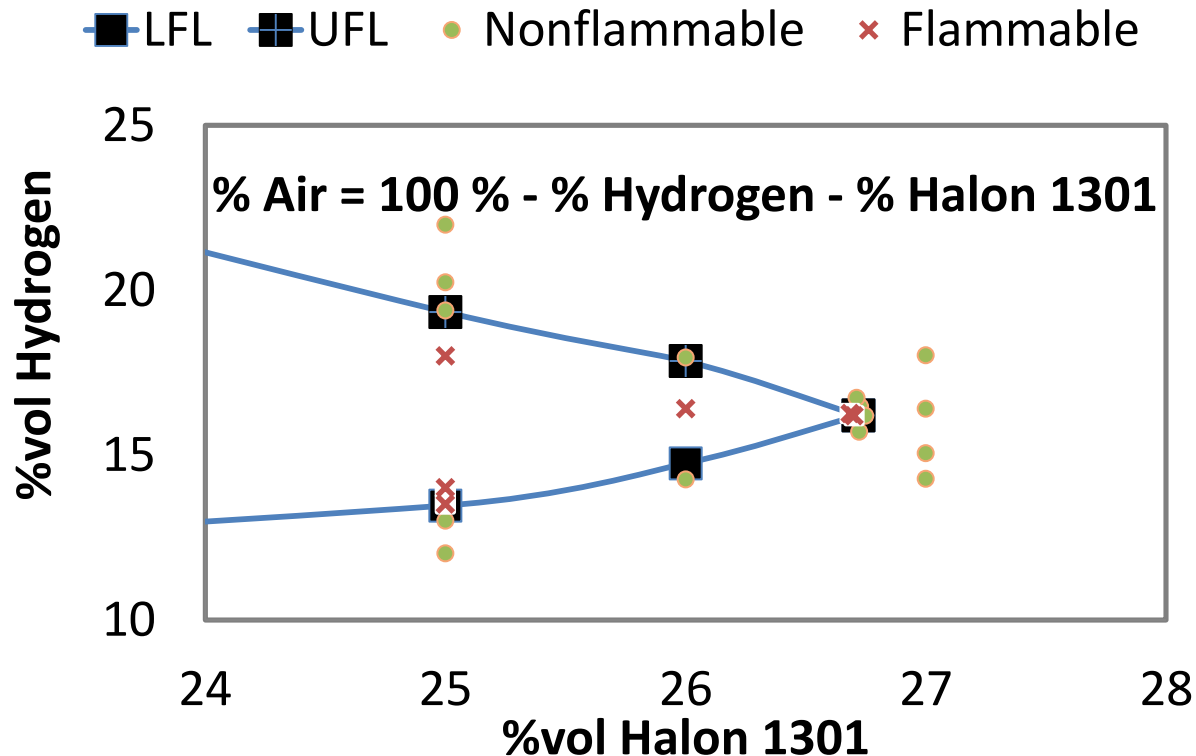
Mixture	MIC, %vol Halon 1301
Hydrogen – Air – Halon 1301	26.72±0.43



100 tests were conducted to determine data used in determining the flammability curve of hydrogen, air, and Halon 1301 mixtures.

Nose Cap MIC of Hydrogen, Air, and Halon 1301 Mixtures

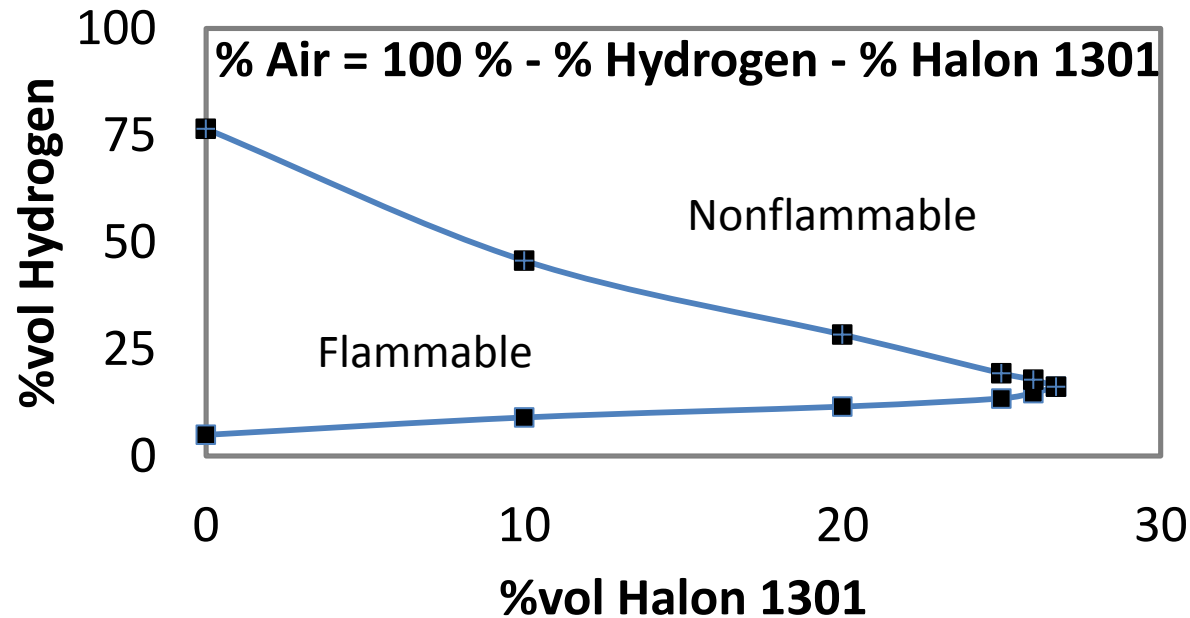
- 21 tests were conducted to determine the minimum inerting concentration of Halon 1301 in hydrogen – air mixtures to be ***26.72±0.43 %vol Halon*** at ***16.2 %vol hydrogen***



The above graph displays where the LFL meets the UFL to form the MIC.

Flammability Curve of Hydrogen, Air, and Halon 1301 Gas Mixtures

- The UFL constricts faster than the LFL as the %vol Halon 1301 increases.
- Inside the curve is considered flammable while outside is considered nonflammable.



Using the above graph, any ratio of hydrogen, air, and Halon 1301 can be determined to be a flammable or nonflammable mixture.

4

Testing Validation

4.1 Validation Overview

4.2 LFL and UFL Validation Analysis

4.2 MIC Validation Analysis

Tester	LFL, %vol Hydrogen	UFL, %vol Hydrogen
Matthew Karp with Mixing Fan (5 % pressure rise)	4.95±0.40	76.52±0.44
Matthew Karp without Mixing Fan (5 % pressure rise)	5.35	78.18
Steve Rehn without Mixing Fan (3 % Pressure Rise) [8]	4.7	78.87
Factory Mutual Research Corporation (Visual Upward Flame Propagation) [9]	4	76
EN 1839 (B) 14 L Vessel (5 % Pressure Rise) [10]	4.2	77
EN 1839 (T) 80 mm Diameter (Visual Method) [10]	3.6	76.6
Herzberg & Cashdollar 8 L Vessel (3 % Pressure Rise) [11]	5±0.5	76.8±0.2
<u>Average</u>	<u>4.56</u>	<u>77.11</u>

LFL and UFL Validation Analysis

- The *averaged LFL and UFL* of the seven experiments are **4.56 %vol hydrogen and 77.11 %vol hydrogen** respectively with a standard deviation of **0.54 %vol hydrogen and 0.88 %vol hydrogen** respectively
- The experimentally determined flammability limits of this study are **4.95±0.40 %vol and 76.52±0.44 %vol hydrogen** for the LFL and UFL respectively.
- The test results of this study are both *within a standard deviation* of the averaged results and therefore validate the test data.

MIC Validation Analysis

- Results from this study found a **MIC of 26.72 %vol Halon 1301** while Factory Mutual Corporation found the **MIC to be 28 %vol Halon 1301** yielding a **4.68 percent difference**
- Factory Mutual Research Corporation used the visual method and this study used the pressure rise method

Tester	MIC, %vol Halon 1301
Matthew Karp with Mixing Fan (5 % Pressure Rise)	26.72±0.43
Factory Mutual Research Corporation (Visual Upward Flame Propagation) [6]	28

Being that these experiments used different testing methods and still yields similar results, it can be concluded that the test results are accurate and reproducible.

5

Flammability Limits and MIC of Li-Ion pBVG and Air Mixtures with and without Halon 1301

5.1 Premixed Lithium-Ion Battery Vent Gas (*Li-Ion pBVG*)
Mixture Constituents

5.2 Overview

5.3 Nose Cap MIC of Li-Ion pBVG, Air, and Halon 1301
Mixtures

5.4 Flammability Curve of Li-Ion pBVG, Air, and Halon 1301
Mixtures

Li-Ion pBVG Mixture Constituents

- The premixed bottled lithium battery vent gas constituents are listed below [4]
- The most prevalent gases are hydrogen, carbon monoxide, and carbon dioxide.

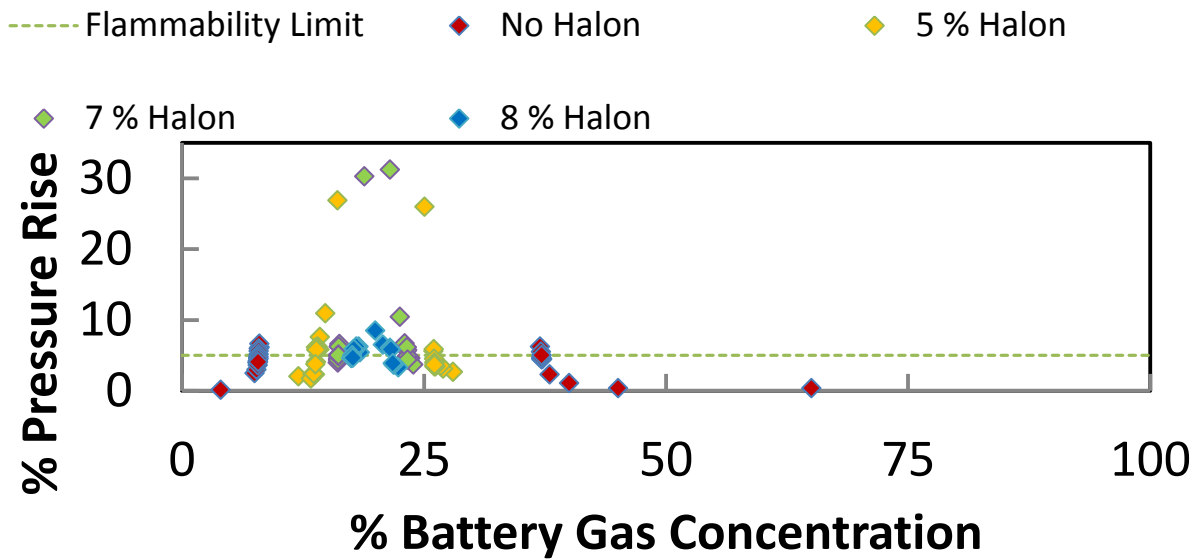
Gas	%vol
Hydrogen	27.60
Carbon Monoxide	22.90
Carbon Dioxide	30.10
Methane	6.37
Propylene	4.48
Ethylene	2.21
Butane	1.57
Ethane	1.17
1-Butane	0.56
Propane	0.27

Rather than collecting Li-Ion battery vent gases, a bottle of premixed battery vent gases (Praxair NI BT1.58X1CASN) was purchased to match the composition of collected battery gases.

Overview

Mixture	LFL, %vol Li-Ion pBVG	UFL, %vol Li-Ion pBVG
Li-Ion pBVG – Air	7.88±0.41	37.14±0.42
Li-Ion pBVG – Air – 5% Halon 1301	13.80±0.49	26.07±0.43
Li-Ion pBVG – Air – 7% Halon 1301	16.15±0.4	23.31±0.44
Li-Ion pBVG – Air – 8% Halon 1301	17.62±0.52	21.84±0.65

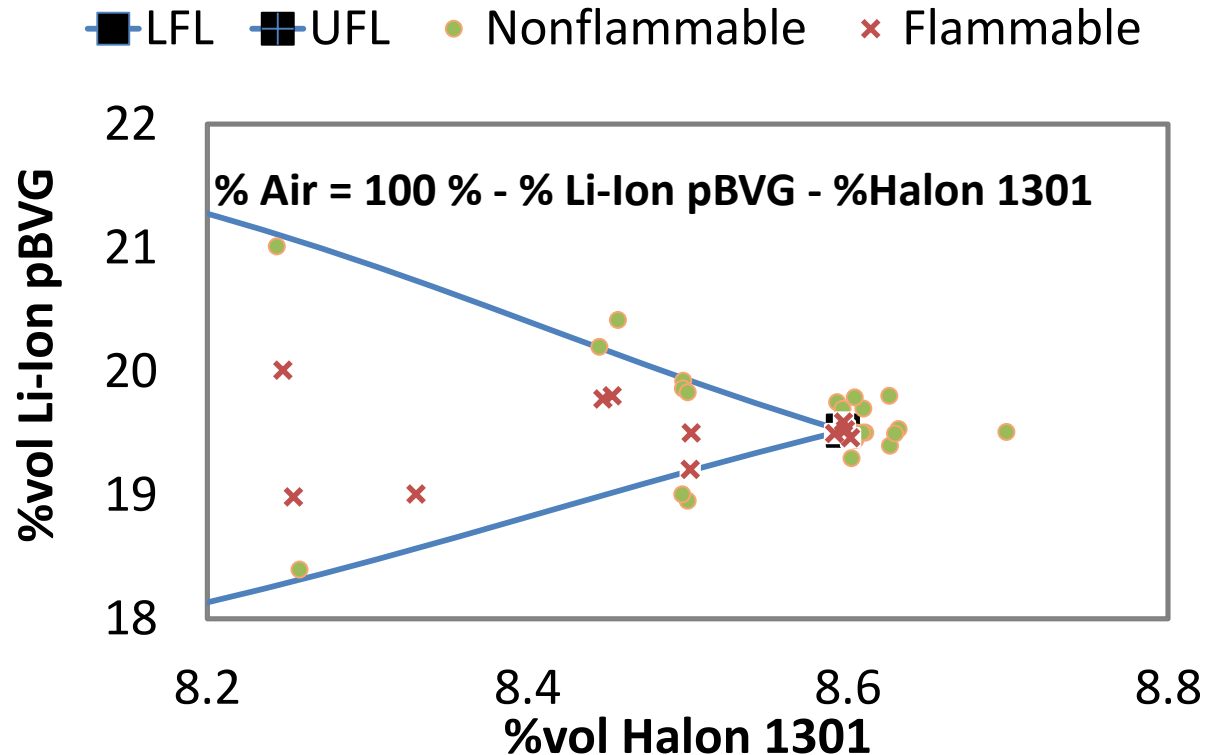
Mixture	MIC, %vol Halon 1301
Lithium Battery Vent Gas – Air – Halon 1301	8.59±0.52



97 tests were conducted to determine data used in determining the flammability curve of Li-Ion pBVG, air, and Halon 1301 mixtures.

Nose Cap MIC of Lithium Battery, Air, and Halon 1301 Mixtures

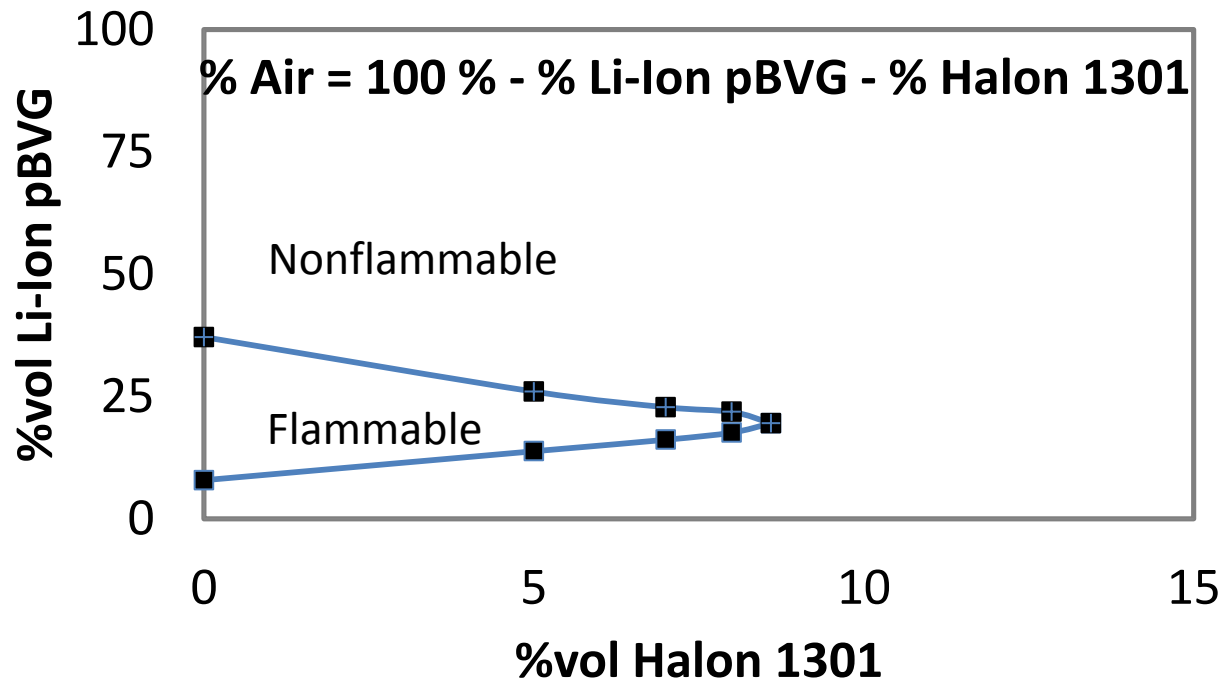
- 34 tests were conducted to determine the minimum inerting concentration of Halon 1301 in mixed Li-Ion pBVG – air mixtures to be ***8.59±0.52 %vol Halon*** at ***19.52 %vol Li-Ion pBVG***



The above graph displays where the LFL meets the UFL to form the MIC.

Flammability Curve of Li-Ion pBVG, Air, and Halon 1301 Mixtures

- The UFL constricts faster than the LFL as the %vol Halon 1301 increases.
- Inside the curve is considered flammable while outside is considered nonflammable.



Using the above graph, any ratio of Li-Ion pBVG, air, and Halon 1301 can be determined to be a flammable or nonflammable mixture.

6

Le Chatelier's Mixing Rule

6.1 Le Chatelier's Mixing Rule [12]

6.2 Comparison of Experimental and Calculated Flammability Limits for Li-Ion pBVG

6.3 Prediction and Analysis for Various States of Charge using Le Chatelier's Mixing Rule

Le Chatelier's Mixing Rule [12]

1. Calculate the constituents of the mixed gas neglecting the presence of air.
2. Create binary gases by combining part of or all of a nonflammable gas with one or more flammable gas and recalculate gas constituents.
3. Record the flammability limits of the mixtures constituents from tables or curves.
4. Calculate the flammability limits of the mixed gas using Le Chatelier's mixing rule equation

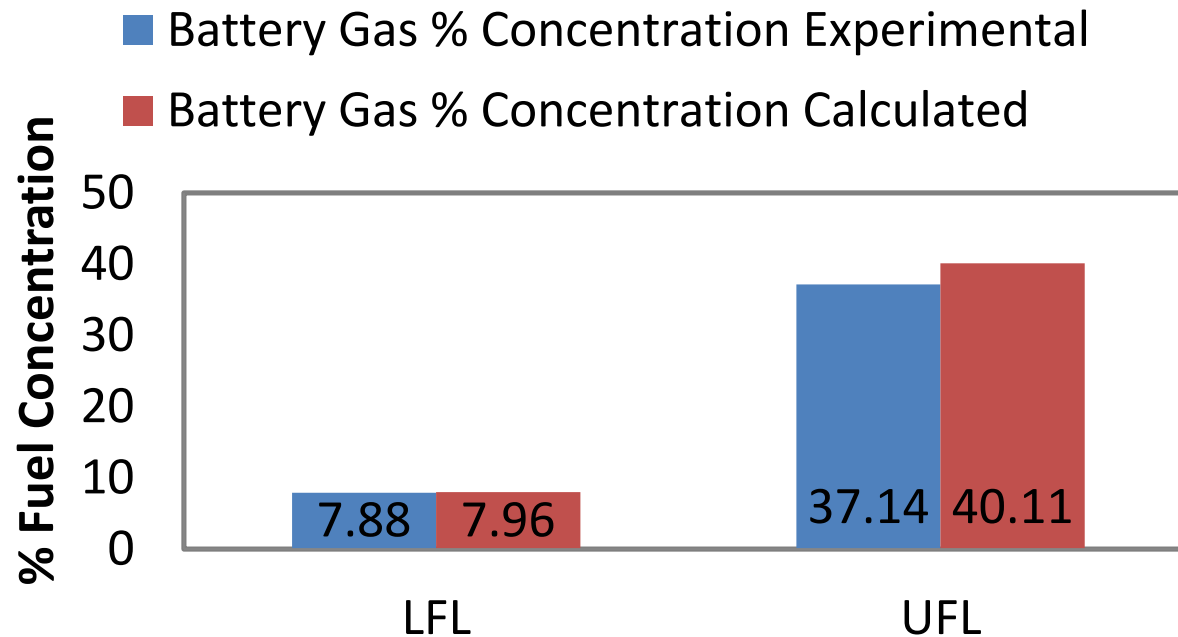
$$L = \frac{100}{\frac{p_1}{N_1} + \frac{p_2}{N_2} + \frac{p_3}{N_3} + \dots}$$

Where L is either the LFL or the UFL of the gas mixture, $p_1, p_2, p_3 \dots$ are the percentages of the mixtures constituents, and $N_1, N_2, N_3 \dots$ are either the LFL or UFL of the individual constituents [12].

*Note that if the constituents do not add up to 100 percent, one could substitute the actual total percentage.

Comparison of Experimental and Calculated Flammability Limits for Li-Ion pBVG

- The LFL has a percent difference of 1.79 %
- The UFL has a percent difference of 4.53 %



Le Chatelier's mixing rule has been shown to be an effective measure for estimating the flammability limits of Li-Ion pBVGes

Prediction and Analysis for Various States of Charge using Le Chatelier's Mixing Rule

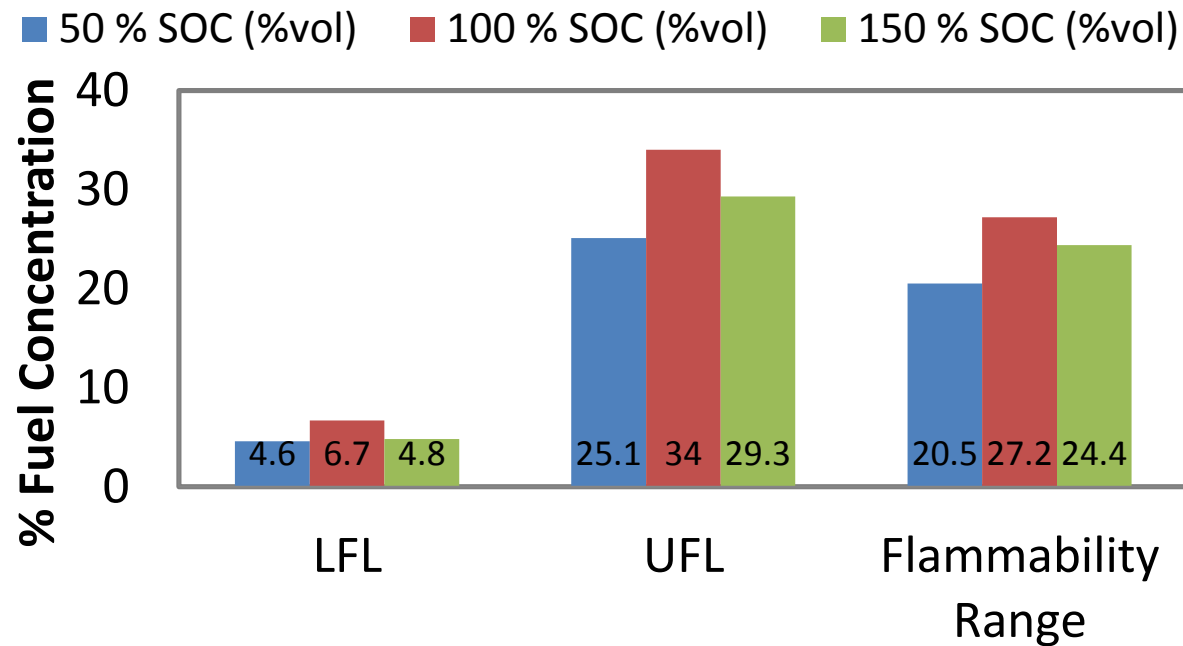
- Collected vent gas constituents from a 7.7 Wh lithium-ion pouch cell at 50 %, 100 %, and 150 % state of charge are used for the predictions listed in the table below [13].

SOC	LFL	UFL	Flammability Range
50 % SOC	4.6	25.1	20.5
100 % SOC	6.8	34.0	27.2
150 % SOC	4.8	29.3	24.4

The above chart predicts the flammability limits of lithium-ion battery thermal runaway vent gas in air at various SOC's.

Prediction and Analysis for Various States of Charge using Le Chatelier's Mixing Rule

- The SOC appears to have a parabolic affect with the widest flammability limits occurring around 100 % SOC
- Flammability limits appear to decrease as the SOC strays from 100 %



The above graph demonstrates the lithium-ion battery thermal runaway vent gas in air is most flammable at 100 % SOC

7

Conclusion

7.1 Comparison of Flammability Limits

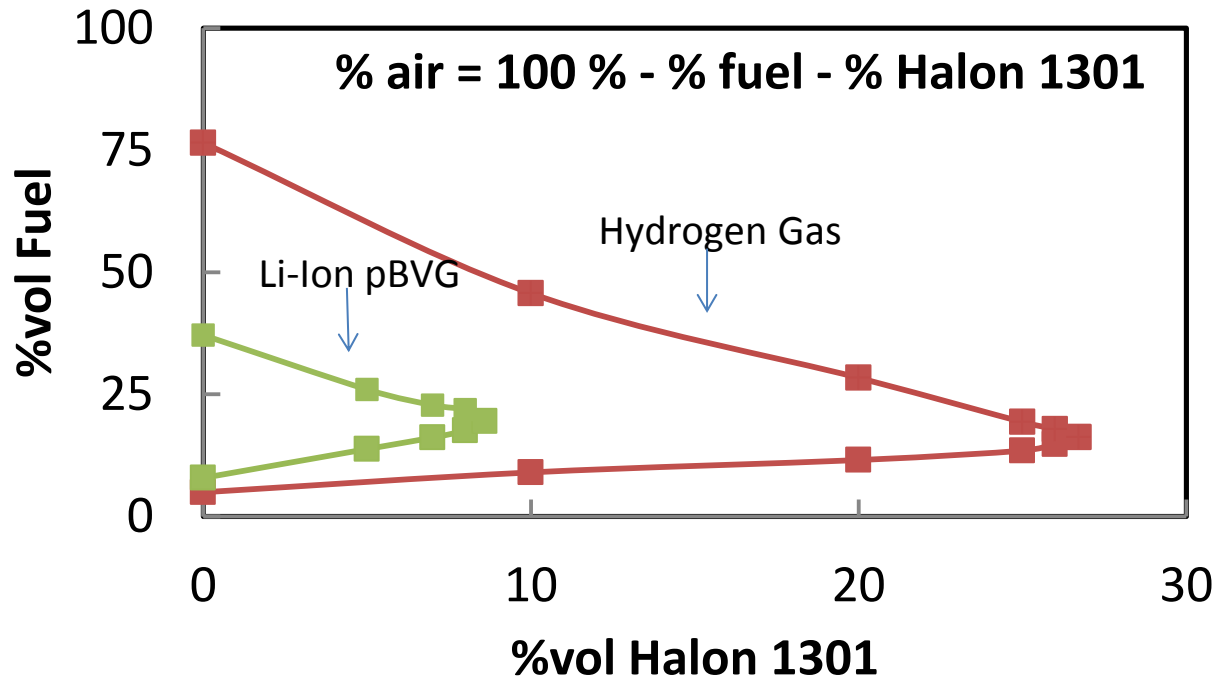
7.3 Aircraft Regulation Sufficiency

7.4 Conclusion

7.5 References

Comparison of Flammability Limits

- Halon 1301 has a greater inerting effect on the LFL of the mixed Li-Ion pBVG compared to hydrogen.
- Halon 1301 has a similar inerting effects on the UFL of the mixed Li-Ion pBVG compared to hydrogen.



The above graph displays the flammability curve of hydrogen, air, and Halon 1301 and Li-Ion pBVG, air, and Halon 1301 in its entirety.

Are Regulations Sufficient?

- Class C cargo compartment utilizes [7]
 - Early fire detection
 - An isolated and built in fire extinguishing system
 - Fire resistant liner
 - 5 %vol Halon 1301 knockdown concentration
 - 3 %vol Halon 1301 sustained for remaining duration of flight

* Title 14 Code of Federal Regulations (CRF) part 25 §25.857
- ***But is that sufficient for lithium-ion battery fires?***

Regulations may not be Sufficient

- Testing indicate the aforementioned concentrations of Halon 1301 is ***not sufficient*** to render lithium battery vent gas and air mixtures nonflammable.
- At ***5 %vol Halon 1301*** the *flammability limits* range from ***13.80 %vol to 26.07 %vol lithium battery vent gas.***
- Testing suggests that ***8.59 %vol Halon 1301*** is required to yield all ratios of the lithium battery vent gas in air inert as indicated by the MIC

Conclusion

- *Reproducible data* is accumulated.
- The results were compared to previous works conducted in the same lab as well as in other labs and *is within a reasonable margin of uncertainty*.
- Federal regulations appear to be inefficient at inerting lithium-ion thermal runaway vent gases in air
- *Le Chatelier's mixing rule* is effective in determining the flammability limits of Li-Ion pBVG and air mixtures

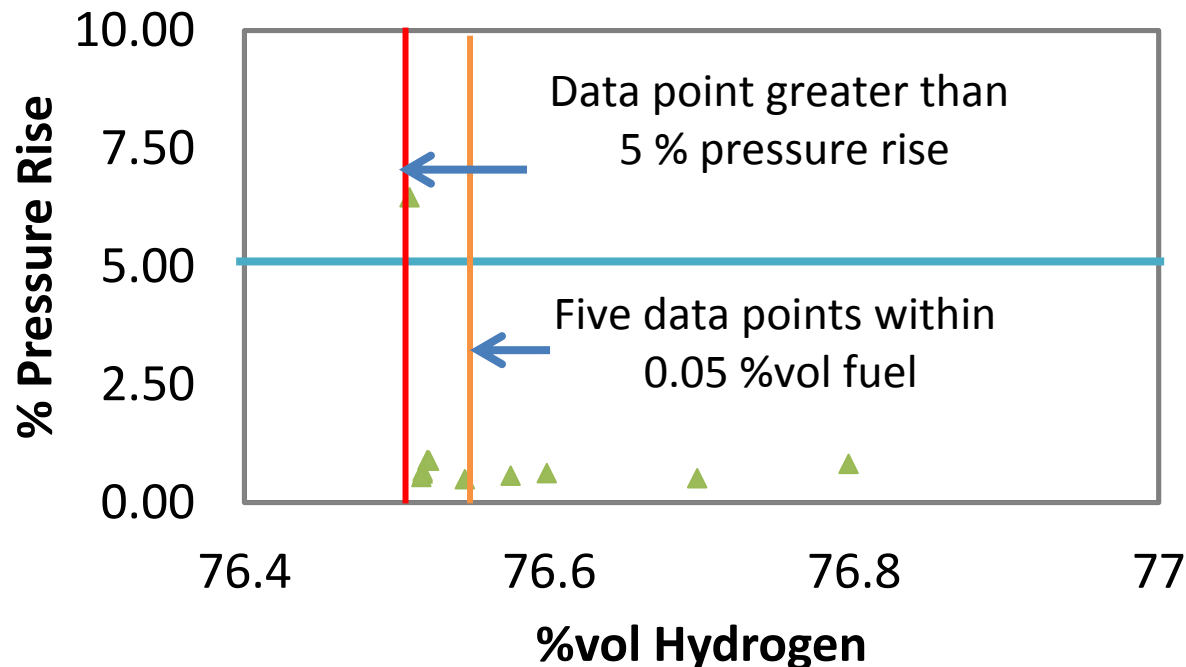
References

- [1] Zabetakis, Michael George. *Flammability characteristics of combustible gases and vapors*. No. BULL-627. Bureau Of Mines Washington DC, 1965.
- [2] Rehn, Steven. *Flammability of hydrogen at sub-atmospheric pressures and reduced oxygen concentrations*. Diss. Rutgers University-Graduate School-New Brunswick, 2014.
- [3] Cashdollar, Kenneth L., et al. "Flammability of methane, propane, and hydrogen gases." *Journal of Loss Prevention in the Process Industries* 13.3 (2000): 327-340.
- [4] Maloney, Thomas. *Lithium Battery Thermal Runaway Vent Gas Analysis*. By Thomas Maloney. Office of Aviation Research, Federal Aviation Administration, 2015.
- [5] IATA. *Lithium Battery Guidance Document*. 7 Jan. 2016. Guidance for complying with provisions applicable to the transport by air of lithium batteries as set out in the 57th Edition of the IATA Dangerous Goods Regulations (DGR).
- [6] *2012 Fire Safety Highlights*. Office of Aviation Research, Federal Aviation Administration, 2012.
- [7] Webster, Harry. *Flammability assessment of bulk-packed, rechargeable lithium-ion cells in transport category aircraft*. Office of Aviation Research, Federal Aviation Administration, 2006
- [8] Rehn, Steven. *Flammability of hydrogen at sub-atmospheric pressures and reduced oxygen concentrations*. Diss. Rutgers University-Graduate School-New Brunswick, 2014.
- [9] Bajpai, Satya N., and John P. Wagner. "Inerting Characteristics of Halogenated Hydrocarbons (Halons)." *Industrial & Engineering Chemistry Product Research and Development* 14.1 (1975): 54-59.
- [10] Schroeder, V., and K. Holtappels. "Explosion characteristics of hydrogen-air and hydrogen-oxygen mixtures at elevated pressures." *International Conference on hydrogen safety, Congress Palace, Pisa, Italy*. 2005.
- [11] Cashdollar, Kenneth L., et al. "Flammability of methane, propane, and hydrogen gases." *Journal of Loss Prevention in the Process Industries* 13.3 (2000): 327-340.
- [12] Coward, Hubert Frank, and George William Jones. *Limits of flammability of gases and vapors*. No. BM-BULL-503. Bureau of Mines Washington DC, 1952.
- [13] Horn, Quinn, and PE Principal Engineer. "Thermal Runaway and Safety of Large Lithium-Ion Battery Systems."

Determining UFL

1. Perform test near flammability limit of 5 % pressure rise.
2. Increase or decrease concentration until test is conducted below 5 % pressure rise
3. Conduct four more tests within 0.05 % fuel concentration of one another without exceeding 5 % pressure rise.
4. Repeat steps 1 through 3 if necessary and average five results.

Hydrogen – Air UFL



The above graph demonstrates how the UFL is determined.

Systematic Error Analysis

1. Percent Gas Concentration

I. 3-4 pressure transducer readings

- Transducer accuracy ± 0.05 psi

II. Leaking vessel

- Leaks at 0.000534 psi/min, test approximately 45 min

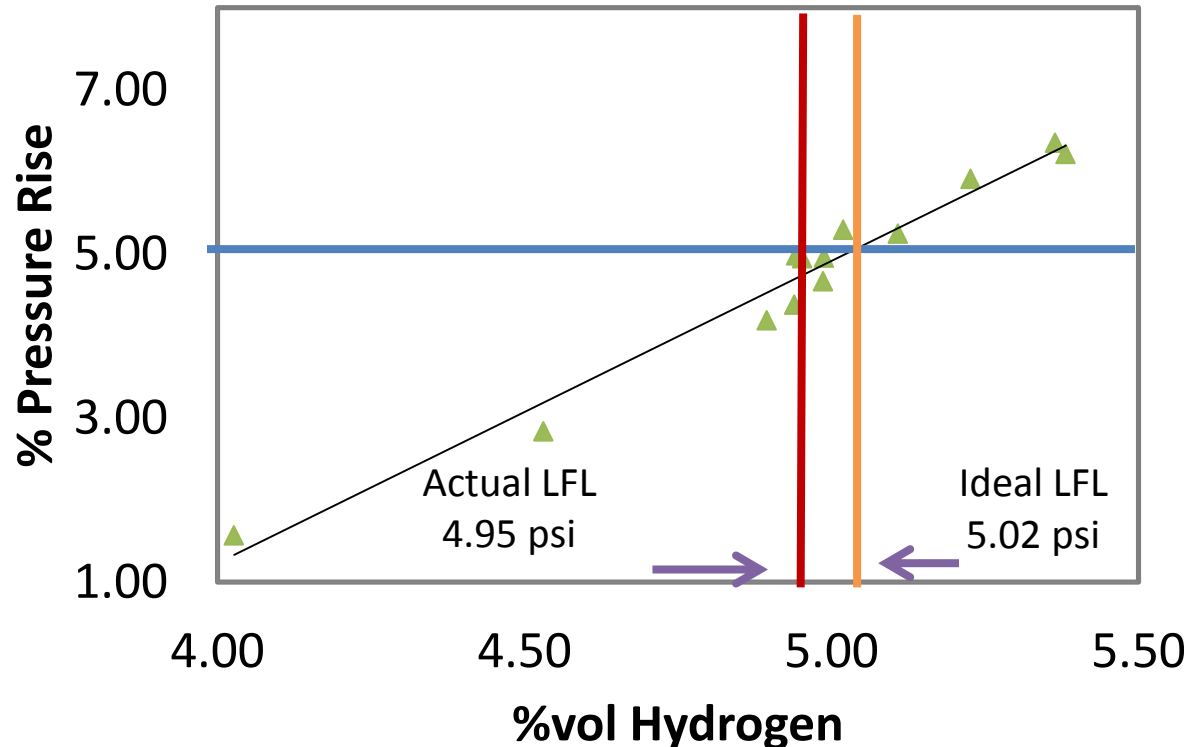
2. Percent Pressure Rise

I. Two pressure transducer readings

- Transducer accuracy ± 0.08 psi

Random Error Analysis

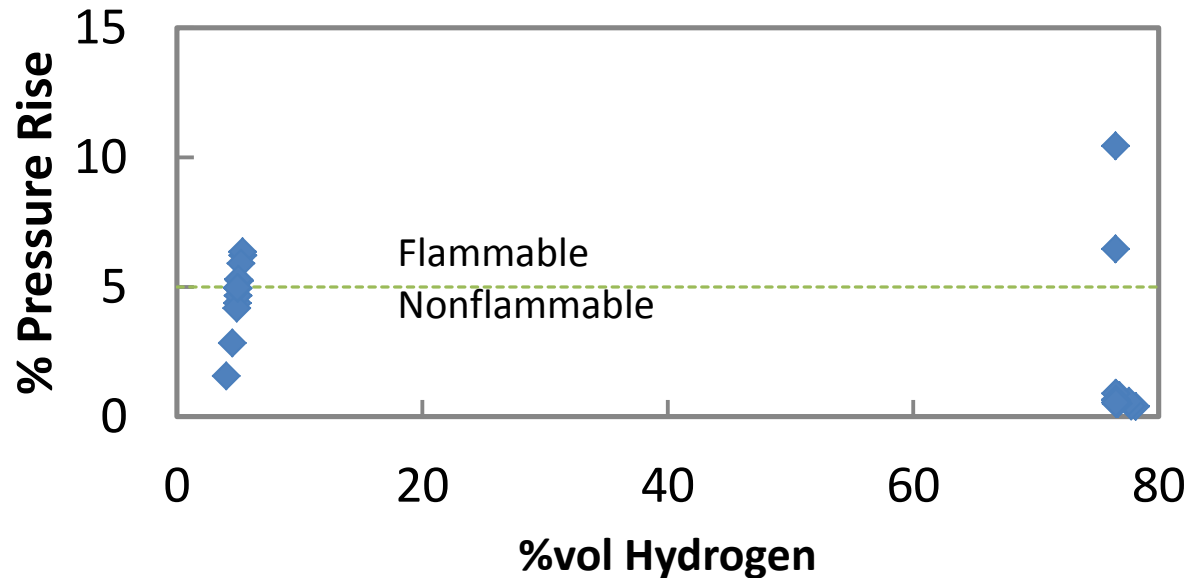
- Random error is determined by *subtracting* the best fit line flammability limit (orange line) by the calculated flammability limit (red line).
- In this example the random error is calculated to be 0.07 psi



The above graph demonstrates how the random error is determined.

LFL and UFL of Hydrogen and Air Mixtures

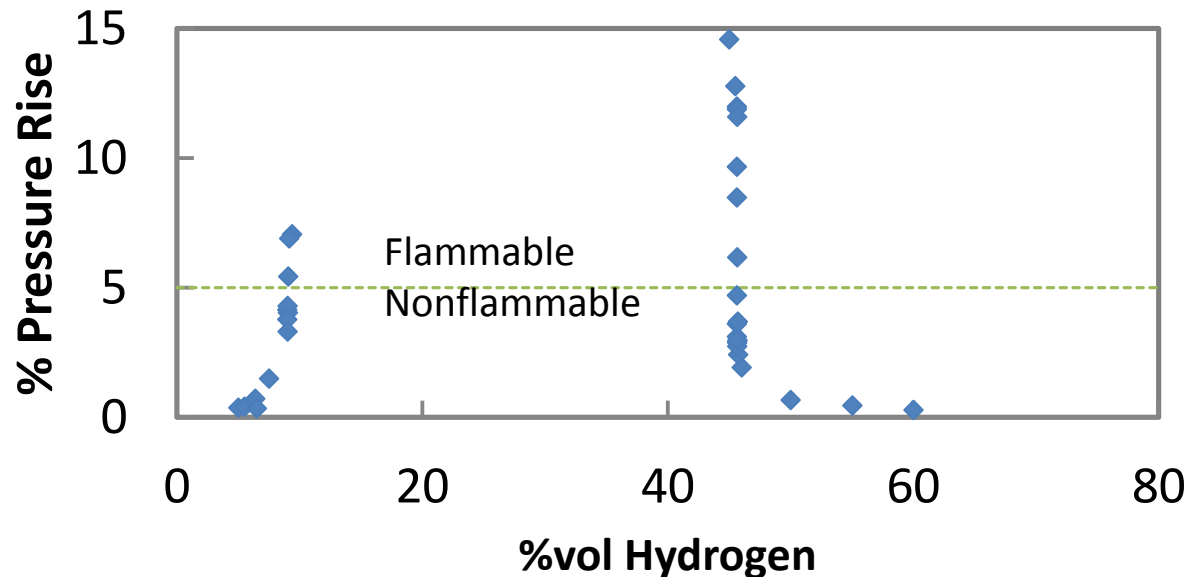
- 15 tests were conducted to determine that the LFL of hydrogen and air mixtures is **4.95 ± 0.40 %vol hydrogen**
- 21 tests were conducted to determine that the UFL of hydrogen and air mixtures is **76.52 ± 0.44 %vol hydrogen**



These data points are used for test validation of experimental procedures.

LFL and UFL of Hydrogen, Air, and 10 %vol Halon 1301 Mixtures

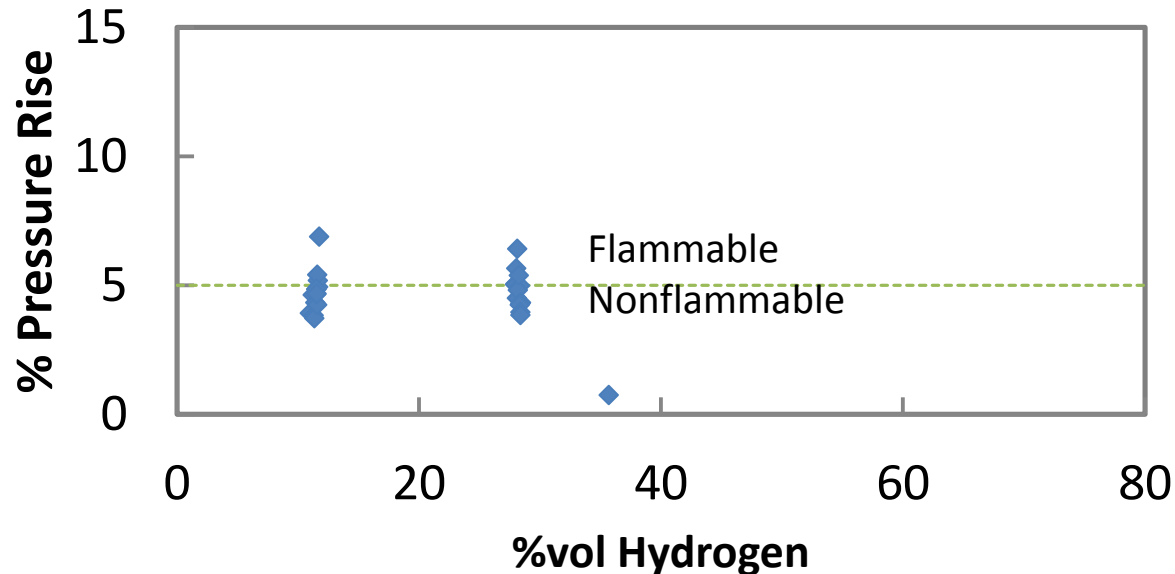
- 13 tests were conducted to determine that the **LFL** of hydrogen – air – Halon 1301 with 10 %vol Halon is ***9.02±0.51 %vol hydrogen***
- 21 tests were conducted to determine that the **UFL** of hydrogen – air – Halon 1301 with 10 %vol Halon is ***45.70±0.41 %vol hydrogen***



Hydrogen is known to have wide flammability limits and is a major contributor to the constituents of Li-Ion BVGs, especially at a SOC at or above ~50 %.

LFL and UFL of Hydrogen, Air, and 20 %vol Halon 1301 Mixtures

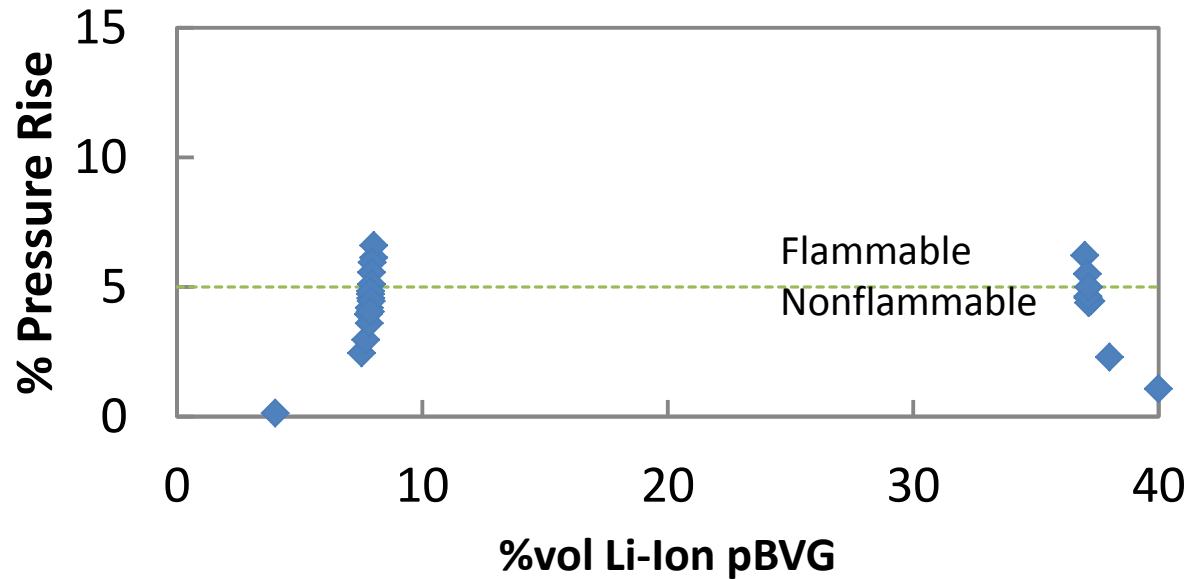
- 14 tests were conducted to determine that the **LFL** of hydrogen – air – Halon 1301 with 20 %vol Halon is ***11.55±0.48 %vol hydrogen***
- 16 tests were conducted to determine that the **UFL** of hydrogen – air – Halon 1301 with 20 %vol Halon is ***28.39±0.47 %vol hydrogen***



Hydrogen is known to have wide flammability limits and is a major contributor to the constituents of Li-Ion BVGeS, especially at a SOC at or above ~50 %.

LFL and UFL of Li-Ion pBVG and Air Mixtures

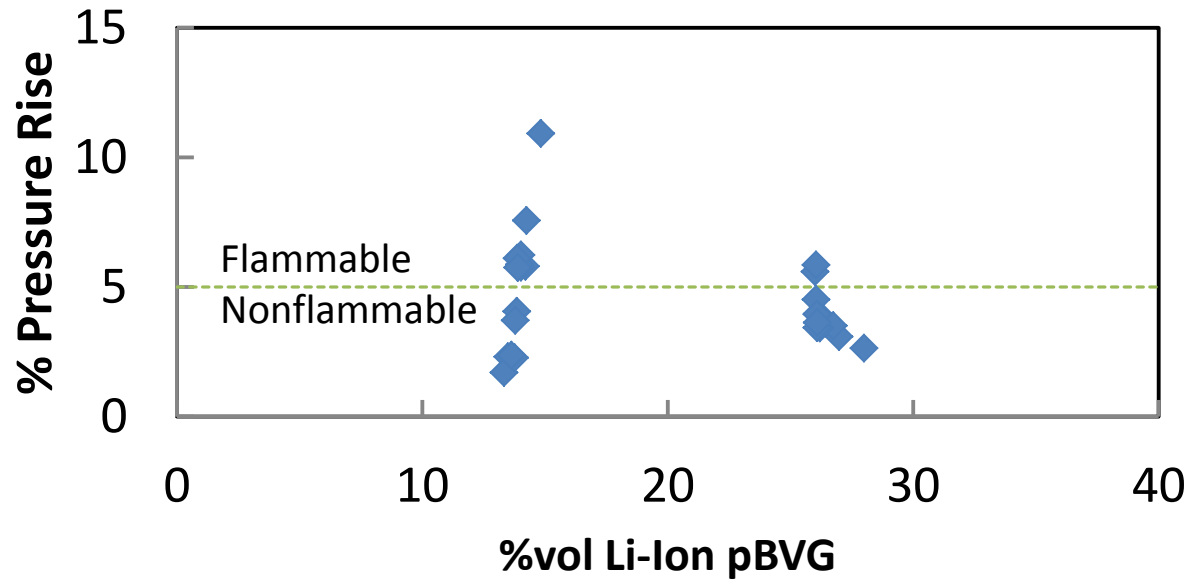
- 16 tests were conducted to determine that the **LFL** of Li-Ion pBVG – air mixture is **7.88 ± 0.41 %vol Li-Ion pBVG**
- 13 tests were conducted to determine that the **UFL** of Li-Ion pBVG – air mixture is **37.14 ± 0.42 %vol Li-Ion pBVG**



These data points are used to determine part of the flammability diagram for Li-Ion pBVG, air, and Halon 1301 mixtures.

LFL and UFL of Li-Ion pBVG, Air, and 5 %vol Halon 1301 Mixtures

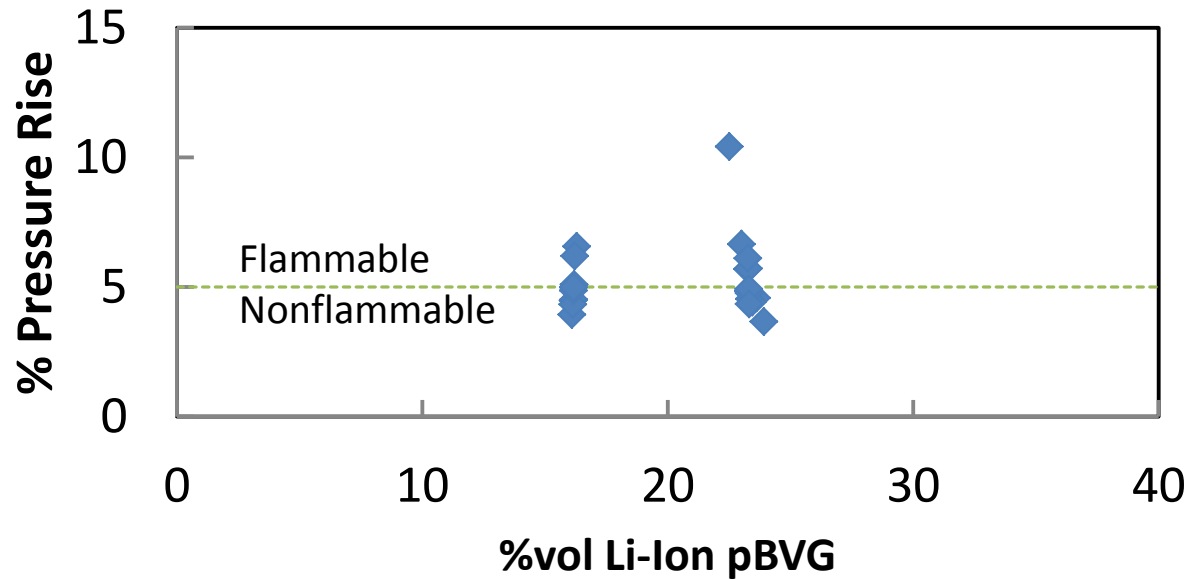
- 17 tests were conducted to determine that the **LFL** of Li-Ion pBVG – air – Halon 1301 5 %vol mixture is **13.80 ± 0.49 %vol Li-Ion pBVG**
- 12 tests were conducted to determine that the **UFL** of Li-Ion pBVG – air – Halon 1301 5 %vol mixture is **26.07 ± 0.43 %vol Li-Ion pBVG**



5 %vol of Halon 1301 is used as the fire extinguishing knockdown concentration in Class C cargo compartments.

LFL and UFL of Li-Ion pBVG, Air, and 7 %vol Halon 1301 Mixtures

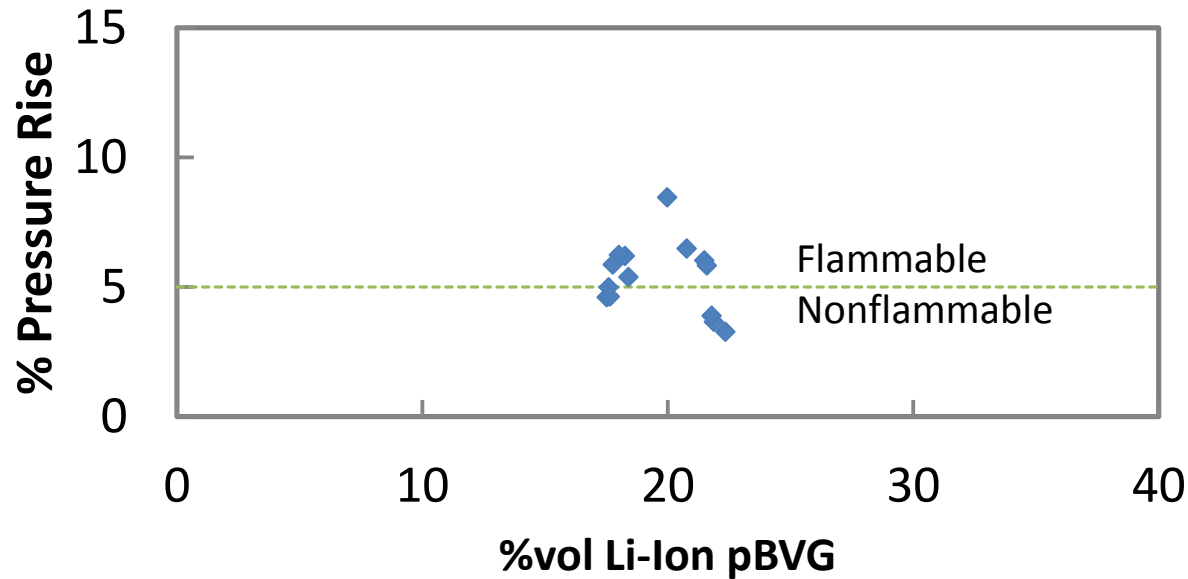
- 10 tests were conducted to determine that the **LFL** of Li-Ion pBVG – air – Halon 1301 7 %vol mixture is **16.15 ± 0.4 %vol Li-Ion pBVG**
- 14 tests were conducted to determine that the **UFL** of Li-Ion pBVG – air – Halon 1301 7 %vol mixture is **23.31 ± 0.44 %vol Li-Ion pBVG**



These data points are used to determine part of the flammability diagram for Li-Ion pBVG, air, and Halon 1301 mixtures.

LFL and UFL of Li-Ion pBVG, Air, and 8 %vol Halon 1301 Mixtures

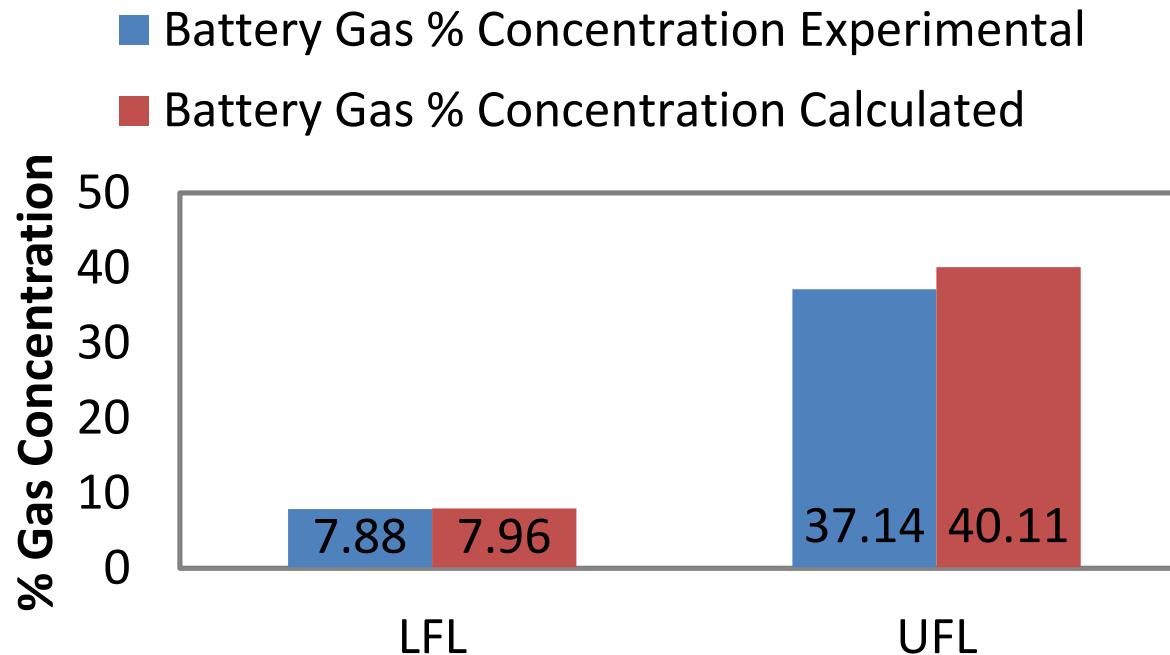
- 8 tests were conducted to determine that the **LFL** of Li-Ion pBVG – air – Halon 1301 8 %vol mixture is **17.62 ± 0.52 %vol Li-Ion pBVG**
- 7 tests were conducted to determine that the **UFL** of Li-Ion pBVG – air – Halon 1301 8 %vol mixture is **21.84 ± 0.65 %vol Li-Ion pBVG**



These data points are used to determine part of the flammability diagram for Li-Ion pBVG, air, and Halon 1301 mixtures.

Review Effectiveness of Le Chatelier's Mixing Rule in Determining Flammability Limits of Li-Ion pBVG in Air Mixtures

- The LFL has a 1.79 % difference
- The UFL has a 4.53 % difference



The above graph demonstrates the effectiveness of Le Chatelier's mixing rule in determining the flammability limits of lithium battery gases in air.

Comparison of Flammability Limits

Mixture	LFL, % Fuel Vol	UFL, % Fuel Vol
Hydrogen – Air	4.95±0.40	76.52±0.44
Hydrogen – Air – 10 % Halon 1301	9.02±0.51	45.70±0.41
Hydrogen – Air – 20 % Halon 1301	11.55±0.48	28.39±0.47
Lithium Battery Vent Gas – Air	7.88±0.41	37.14±0.42
Lithium Battery Vent Gas – Air – 5% Halon 1301	13.80±0.49	26.07±0.43
Lithium Battery Vent Gas – Air – 7% Halon 1301	16.15±0.4	23.31±0.44
Lithium Battery Vent Gas – Air – 8% Halon 1301	17.62±0.52	21.84±0.65

Mixture	MIC, % Halon 1301 Vol
Hydrogen – Air – Halon 1301	26.72±0.43
Lithium Battery Vent Gas – Air – Halon 1301	8.59±0.52

The above data points are used to determine the flammability curve of hydrogen, air, and Halon 1301 and Li-Ion pBVG, air, and Halon 1301.

Future Work

- Knowledge of flammability limits and flammability curves are essential in analyzing and mitigating the risks associated with various gases
- There is still more to study in the field of lithium battery vent gas flammability for the application of aircraft fire safety
 - Testing can be conducted to determine the flammability limits and maximum pressure rise of lithium batteries of varying sizes or cell chemistry at varying states of charge.
 - Testing can also be conducted to determine the effectiveness of various gases or gas mixtures in inerting lithium battery vent gases.
- Flammability testing is laborious. Therefore, there are plans to automate the test apparatus. This will allow for safer, more accurate, and quicker testing while reducing labor.