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

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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

<table>
<thead>
<tr>
<th>An increase in the variable...</th>
<th>Causes the flammability limits to...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spark Energy [1]</td>
<td>Expand</td>
</tr>
<tr>
<td>Ambient Temperature [1]</td>
<td>Expand</td>
</tr>
<tr>
<td>Ambient Pressure [2]</td>
<td>Constrict</td>
</tr>
<tr>
<td>Pressure Vessel Volume [3]</td>
<td>Constrict</td>
</tr>
</tbody>
</table>

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*. 
Pressure Transducer 0-15 psi partial pressures

21.7 Liter 316L stainless steel pressure vessel

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

High speed and low speed data acquisition system

Thermocouple
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.

<table>
<thead>
<tr>
<th>Gas</th>
<th>%vol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>27.60</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>22.90</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>30.10</td>
</tr>
<tr>
<td>Methane</td>
<td>6.37</td>
</tr>
<tr>
<td>Propylene</td>
<td>4.48</td>
</tr>
<tr>
<td>Ethylene</td>
<td>2.21</td>
</tr>
<tr>
<td>Butane</td>
<td>1.57</td>
</tr>
<tr>
<td>Ethane</td>
<td>1.17</td>
</tr>
<tr>
<td>1-Butane</td>
<td>0.56</td>
</tr>
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<td>0.27</td>
</tr>
</tbody>
</table>

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
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.

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.

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

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

<table>
<thead>
<tr>
<th>Mixture</th>
<th>LFL, %vol Hydrogen</th>
<th>UFL, %vol Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen – Air</td>
<td>4.95±0.40</td>
<td>76.52±0.44</td>
</tr>
<tr>
<td>Hydrogen – Air – 10 % Halon 1301</td>
<td>9.02±0.51</td>
<td>45.70±0.41</td>
</tr>
<tr>
<td>Hydrogen – Air – 20 % Halon 1301</td>
<td>11.55±0.48</td>
<td>28.39±0.47</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Mixture</th>
<th>MIC, %vol Halon 1301</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen – Air – Halon 1301</td>
<td>26.72±0.43</td>
</tr>
</tbody>
</table>
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 \(26.72 \pm 0.43 \% \text{vol Halon} \) at \(16.2 \% \text{vol hydrogen}\).

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

- The averaged LFL and UFL of the seven experiments are 4.56 %\textit{vol hydrogen} and 77.11 %\textit{vol hydrogen} respectively with a standard deviation of 0.54 %\textit{vol hydrogen} and 0.88 %\textit{vol hydrogen} respectively.

- The experimentally determined flammability limits of this study are 4.95±0.40 %\textit{vol} and 76.52±0.44 %\textit{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

<table>
<thead>
<tr>
<th>Tester</th>
<th>MIC, %vol Halon 1301</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matthew Karp with Mixing Fan (5 % Pressure Rise)</td>
<td>26.72±0.43</td>
</tr>
</tbody>
</table>

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.

<table>
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<tr>
<th>Gas</th>
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### Overview

<table>
<thead>
<tr>
<th>Mixture</th>
<th>LFL, %vol Li-Ion pBVG</th>
<th>UFL, %vol Li-Ion pBVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-Ion pBVG – Air</td>
<td>7.88±0.41</td>
<td>37.14±0.42</td>
</tr>
<tr>
<td>Li-Ion pBVG – Air – 5% Halon 1301</td>
<td>13.80±0.49</td>
<td>26.07±0.43</td>
</tr>
<tr>
<td>Li-Ion pBVG – Air – 7% Halon 1301</td>
<td>16.15±0.4</td>
<td>23.31±0.44</td>
</tr>
<tr>
<td>Li-Ion pBVG – Air – 8% Halon 1301</td>
<td>17.62±0.52</td>
<td>21.84±0.65</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mixture</th>
<th>MIC, %vol Halon 1301</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium Battery Vent Gas – Air – Halon 1301</td>
<td>8.59±0.52</td>
</tr>
</tbody>
</table>

97 tests were conducted to determine date 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 $8.59 \pm 0.52 \%_{\text{vol}}$ Halon at $19.52 \%_{\text{vol}}$ Li-Ion pBVG

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

\[
L = \frac{100}{\frac{p_1}{N_1} + \frac{p_2}{N_2} + \frac{p_3}{N_3} + \ldots}
\]

Where \( L \) is either the LFL or the UFL of the gas mixture, \( p_1, p_2, p_3 \ldots \) are the percentages of the mixtures constituents, and \( N_1, N_2, N_3 \ldots \) 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].

<table>
<thead>
<tr>
<th>SOC</th>
<th>LFL</th>
<th>UFL</th>
<th>Flammability Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 % SOC</td>
<td>4.6</td>
<td>25.1</td>
<td>20.5</td>
</tr>
<tr>
<td>100 % SOC</td>
<td>6.8</td>
<td>34.0</td>
<td>27.2</td>
</tr>
<tr>
<td>150 % SOC</td>
<td>4.8</td>
<td>29.3</td>
<td>24.4</td>
</tr>
</tbody>
</table>

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


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.

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.
15 tests were conducted to determine that the LFL of hydrogen and air mixtures is $4.95\pm0.40 \%\text{vol hydrogen}$

21 tests were conducted to determine that the UFL of hydrogen and air mixtures is $76.52\pm0.44 \%\text{vol hydrogen}$

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 $9.02 \pm 0.51 \%vol$ hydrogen
- 21 tests were conducted to determine that the UFL of hydrogen – air – Halon 1301 with 10 %vol Halon is $45.70 \pm 0.41 \%vol$ 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 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 \(11.55 \pm 0.48\) %vol hydrogen.
- 16 tests were conducted to determine that the UFL of hydrogen – air – Halon 1301 with 20 %vol Halon is \(28.39 \pm 0.47\) %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 \(\sim 50\%\).
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 $7.88 \pm 0.41 \%vol \text{ Li-Ion pBVG}$
- 13 tests were conducted to determine that the UFL of Li-Ion pBVG – air mixture is $37.14 \pm 0.42 \%vol \text{ Li-Ion pBVG}$

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 $13.80 \pm 0.49 \% \text{vol Li-ion pBVG}$
- 12 tests were conducted to determine that the UFL of Li-ion pBVG – air – Halon 1301 5 %vol mixture is $26.07 \pm 0.43 \% \text{vol Li-ion pBVG}$

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 $16.15 \pm 0.4 \text{%vol Li-ion pBVG}$
- 14 tests were conducted to determine that the UFL of Li-ion pBVG – air – Halon 1301 7 %vol mixture is $23.31 \pm 0.44 \text{%vol Li-ion pBVG}$

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 $17.62 \pm 0.52 \% \text{vol Li-Ion pBVG}$
- 7 tests were conducted to determine that the UFL of Li-Ion pBVG – air – Halon 1301 8 %vol mixture is $21.84 \pm 0.65 \% \text{vol Li-Ion pBVG}$

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

<table>
<thead>
<tr>
<th>Mixture</th>
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<tr>
<td>Lithium Battery Vent Gas – Air – 5% Halon 1301</td>
<td>13.80±0.49</td>
<td>26.07±0.43</td>
</tr>
<tr>
<td>Lithium Battery Vent Gas – Air – 7% Halon 1301</td>
<td>16.15±0.4</td>
<td>23.31±0.44</td>
</tr>
<tr>
<td>Lithium Battery Vent Gas – Air – 8% Halon 1301</td>
<td>17.62±0.52</td>
<td>21.84±0.65</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mixture</th>
<th>MIC, % Halon 1301 Vol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen – Air – Halon 1301</td>
<td>26.72±0.43</td>
</tr>
<tr>
<td>Lithium Battery Vent Gas – Air – Halon 1301</td>
<td>8.59±0.52</td>
</tr>
</tbody>
</table>

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.