Flammability of Mixed Battery Gases and the Inerting Effects of Halon 1301

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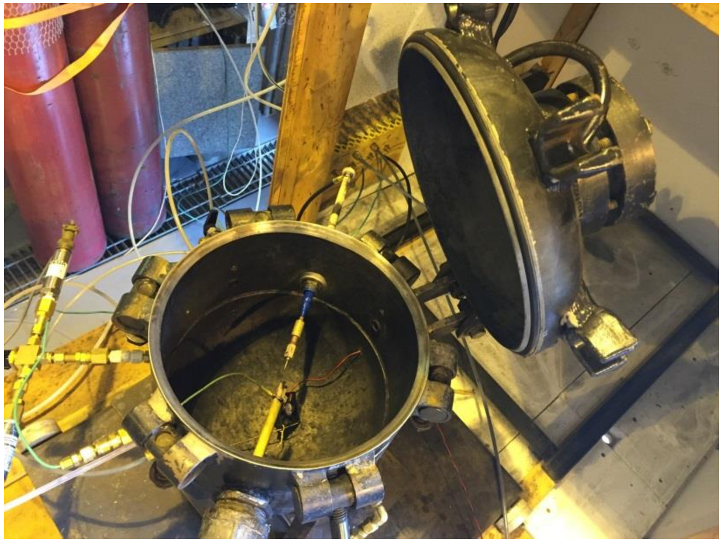
Background

- Lithium batteries are commonly used in small electrical devices and shipped in the cargo holds of passenger and freighter aircraft.
- Flammability limits and the minimum inerting concentration gases are fundamentally essential in accurately predicting risks of explosion associated with flammable gases.



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 a 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

Scope

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

Lithium Ion Battery Vent Gas Mixture

- 30.1% CO_2
- 27.6% H_2
- 22.9% CO
- 6.37% CH_4
- 4.48% C_3H_6
- 2.21% C_2H_4
- 1.57% C_4H_{10}
- 1.17% C_2H_6
- .56% C_4H_8
- .268% C_3H_8

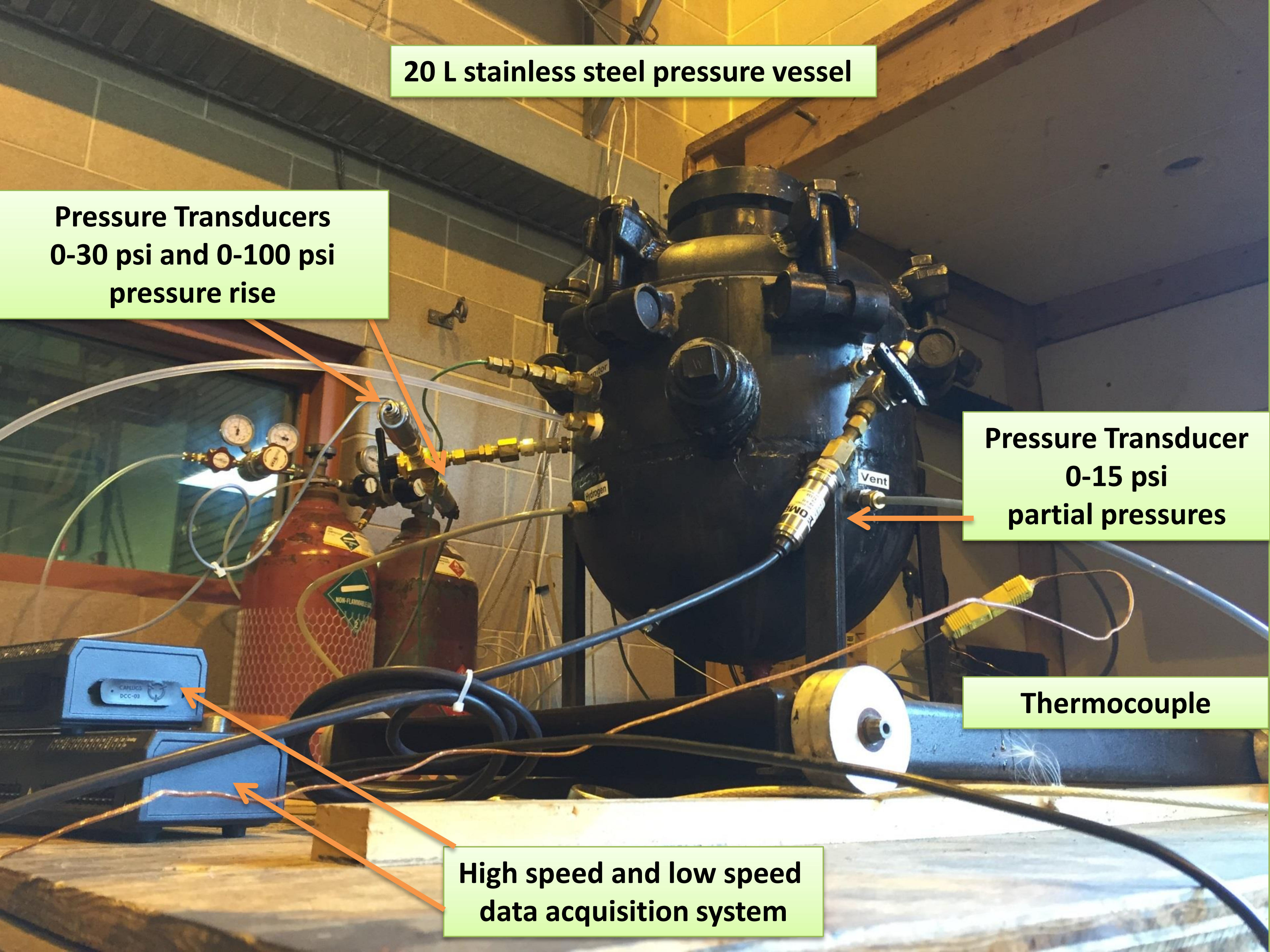
The lithium ion battery vent gas mixture is listed by percent concentration. *

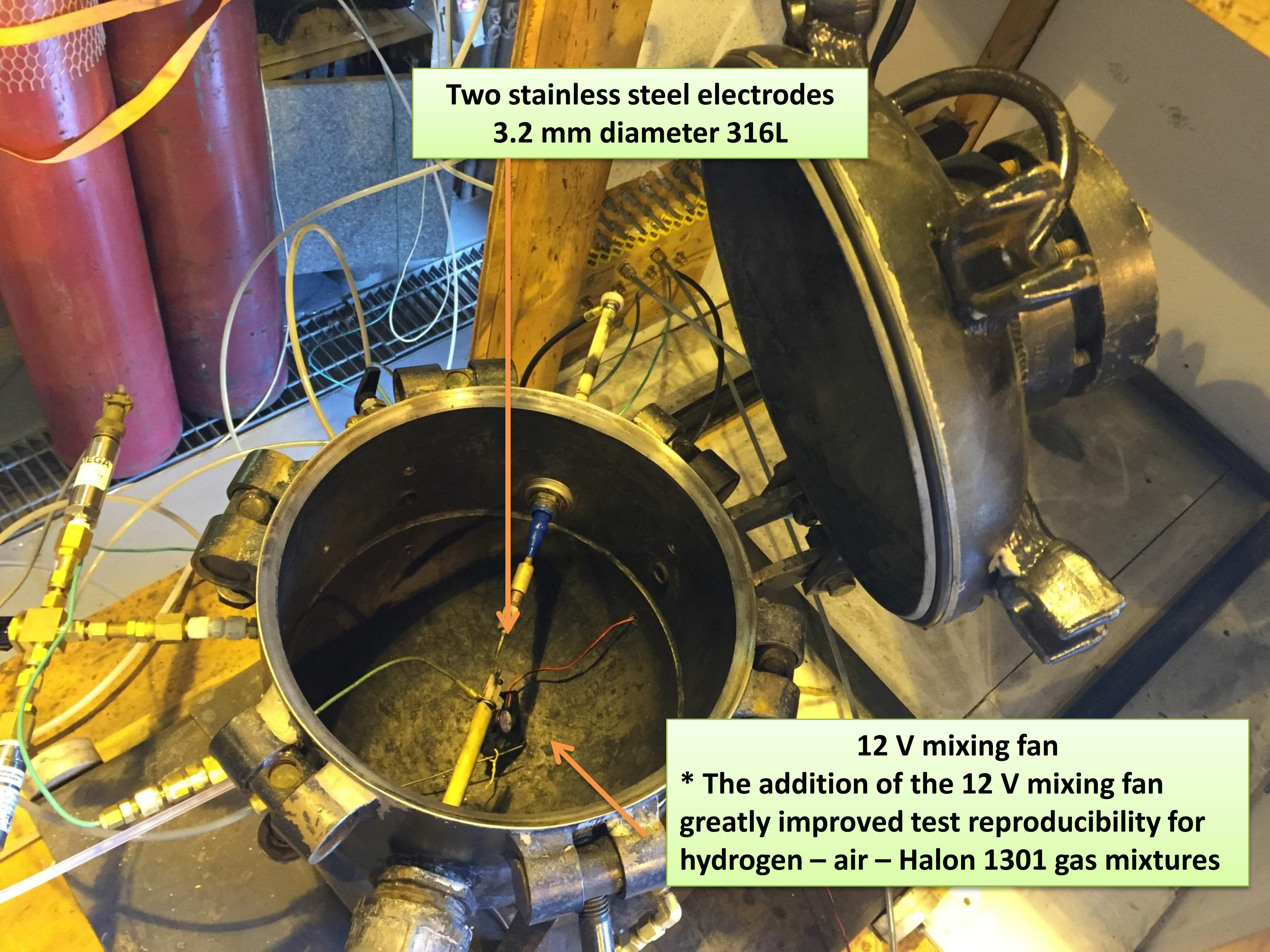
The three most prevalent gases are carbon dioxide (30.1 %), hydrogen (27.6 %), and carbon monoxide (22.9).

"The aircraft hazards of flammable gasses produced by lithium batteries in thermal runaway" *
Presented at the ICAO Multidisciplinary meeting on 8/10/2015
Tom Maloney

Scope

- Experimentally determine LFL and UFL of *premixed lithium ion battery vent gases* – air mixtures
- Experimentally determine the inerting effects of Halon 1301 on *premixed lithium ion battery vent gases* – air mixtures
  - LFL and UFL with 10 % Halon 1301
  - LFL and UFL with 20 % Halon 1301
  - MIC of Halon 1301 on battery gas – air mixtures


20 L 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
Vent
Hydrogen


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

Testing Apparatus

The 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

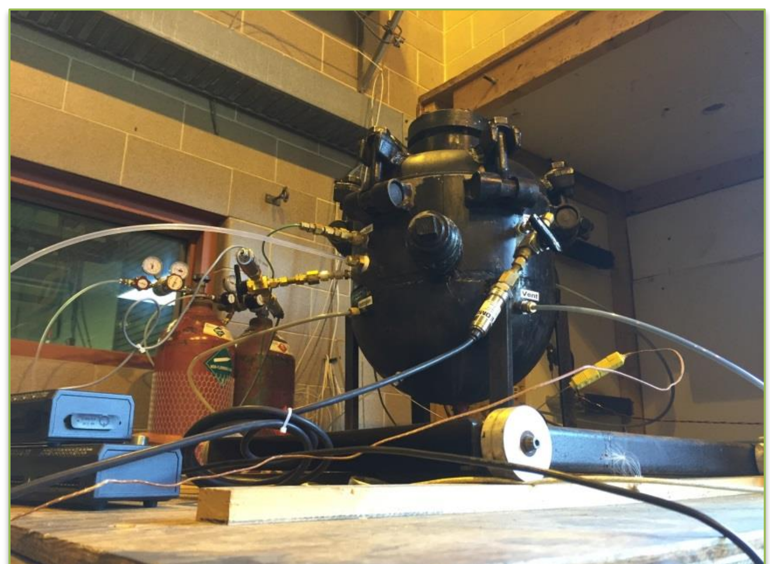
Testing Procedure Summary

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 until mixture is quiescent
5. Ignite mixture
6. Measure pressure rise
7. Analyze data
8. Repeat steps 1 through 7

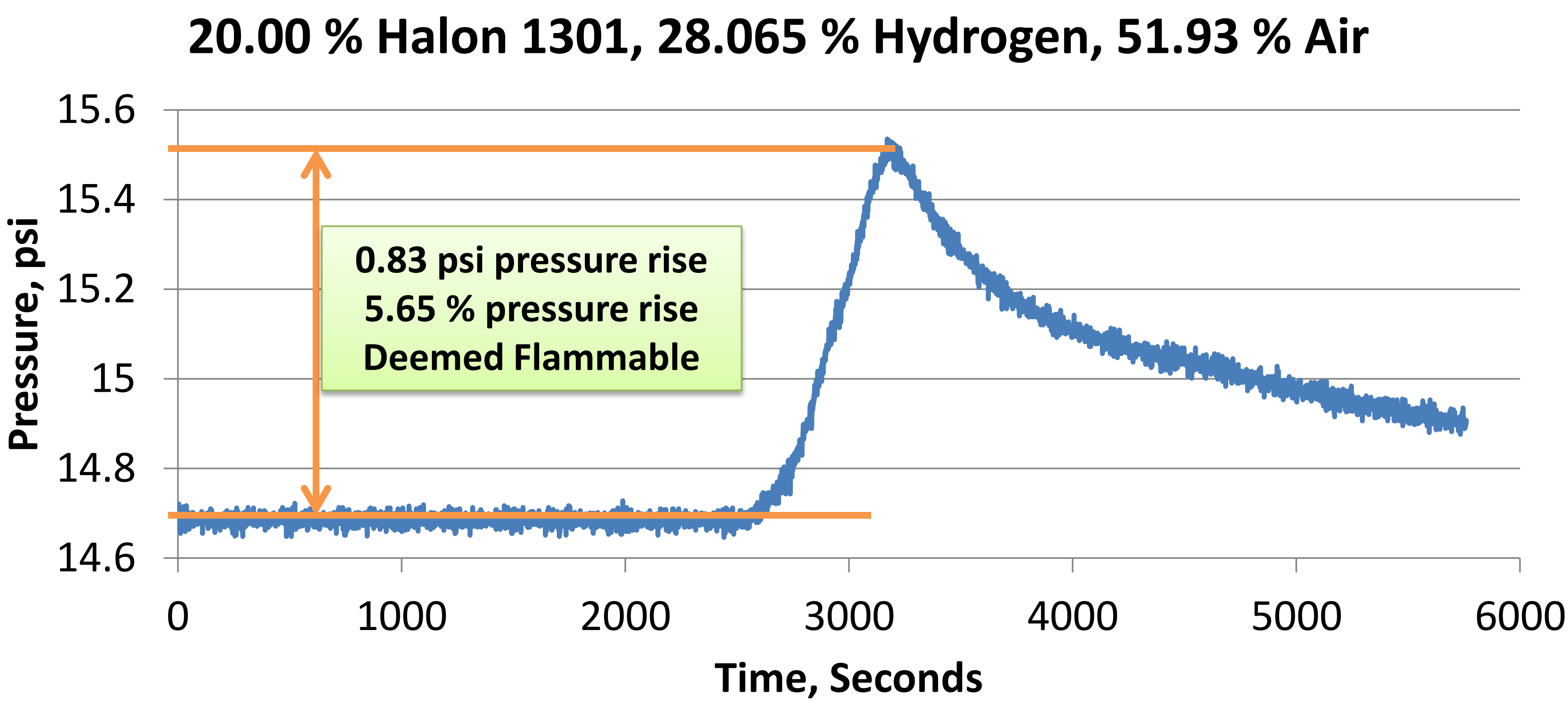
Test Criterion

- Previous tests have set the determining flammability limit at varying percent pressure rises
  - ASTM International E2079 uses 7 % pressure rise
  - European Standard EN 1839 uses 5 % pressure rise
  - Steve Rehn FAA uses a 3 % pressure rise
- I will use a 5 % pressure rise



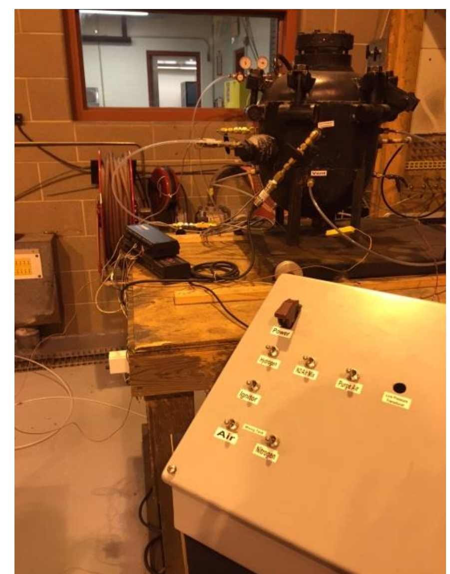
Test Example

This test started at 14.68 psi and rose to 15.51 psi after ignition for a pressure rise of 0.83 psi and a *percent pressure rise of 5.65 %.* It is greater than 5 %, therefore, this particular test is considered flammable.



Determining Flammability Limits

1. Increase or decrease concentration by 0.05 % intervals until a non flammable mixture is tested *
2. Test five non flammable mixtures within 0.05 % concentration of one another to determine flammability limit *
   - A flammable mixture result requires additional repetition of steps 1 and 2 until five non flammable tests are conducted *
3. Average five tests to get result

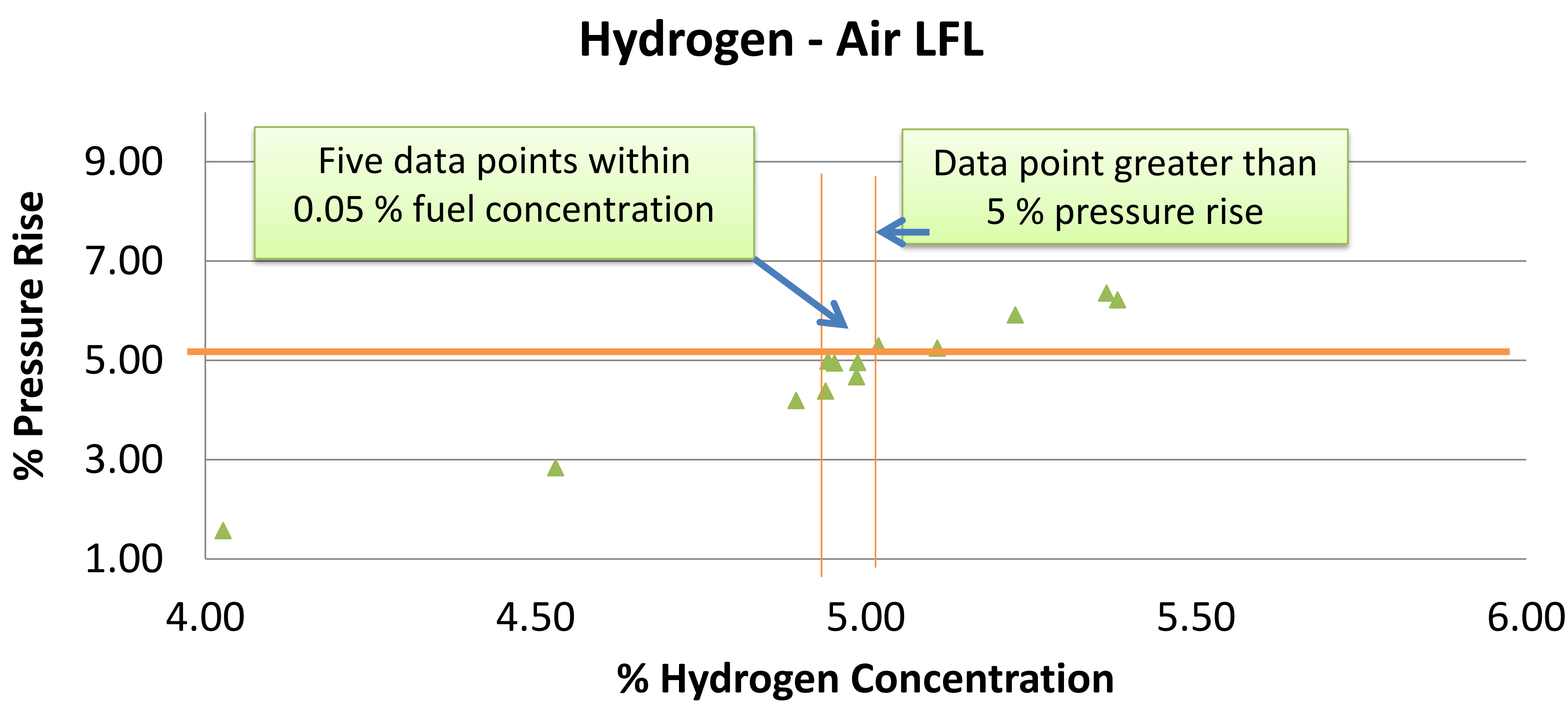


* Based off the European Standard EN 1839

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.

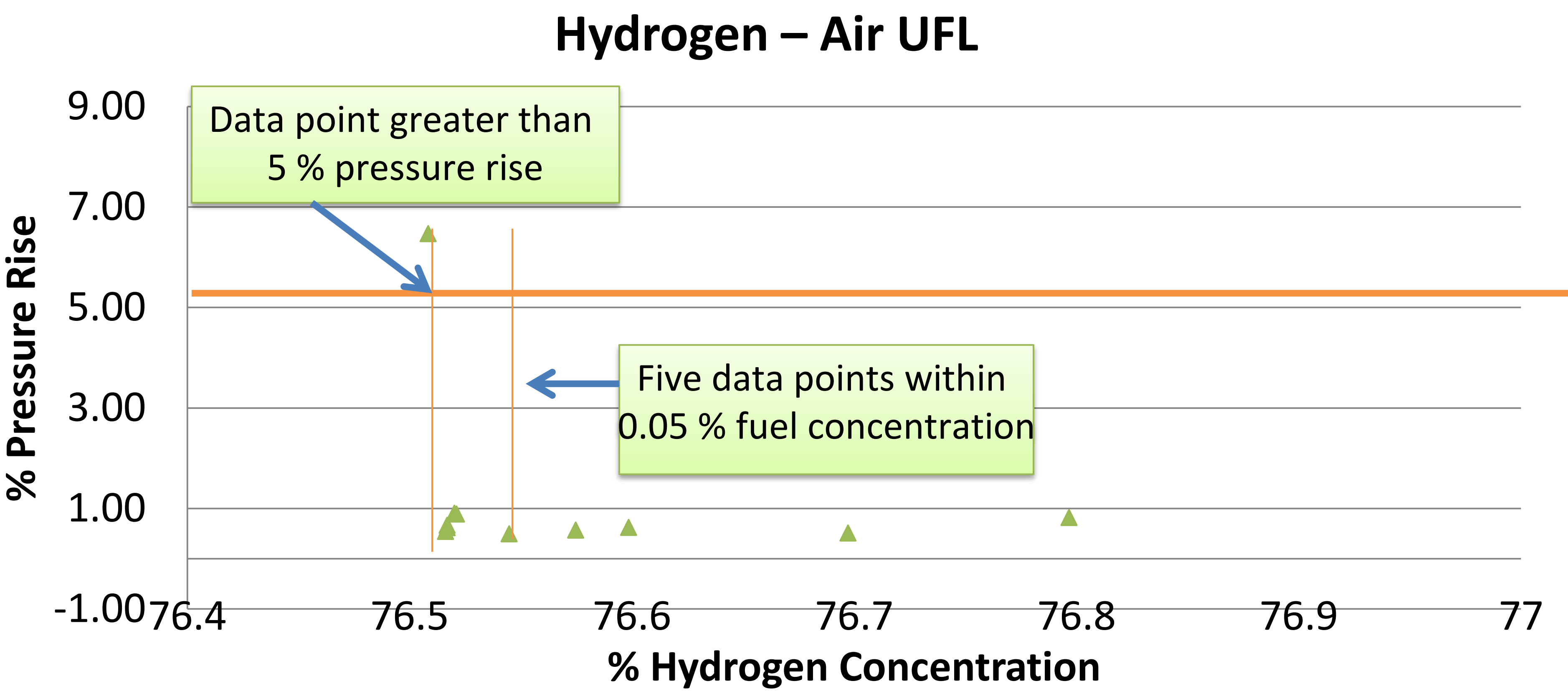
* European Standard EN 1839



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.

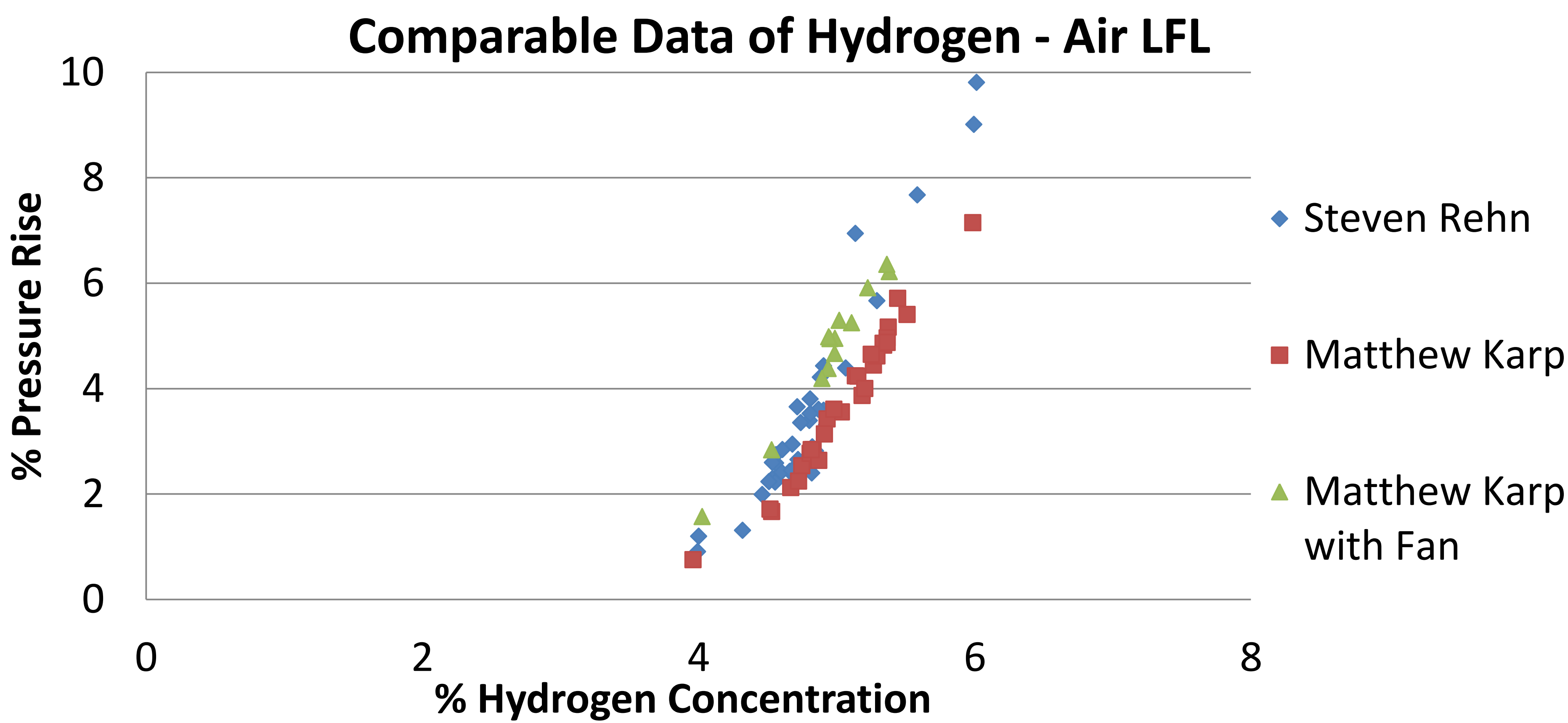
* European Standard EN 1839



Testing validation and data points to determine LFL of hydrogen – air mixture

Data points determining the LFL of hydrogen air mixtures are shown below.

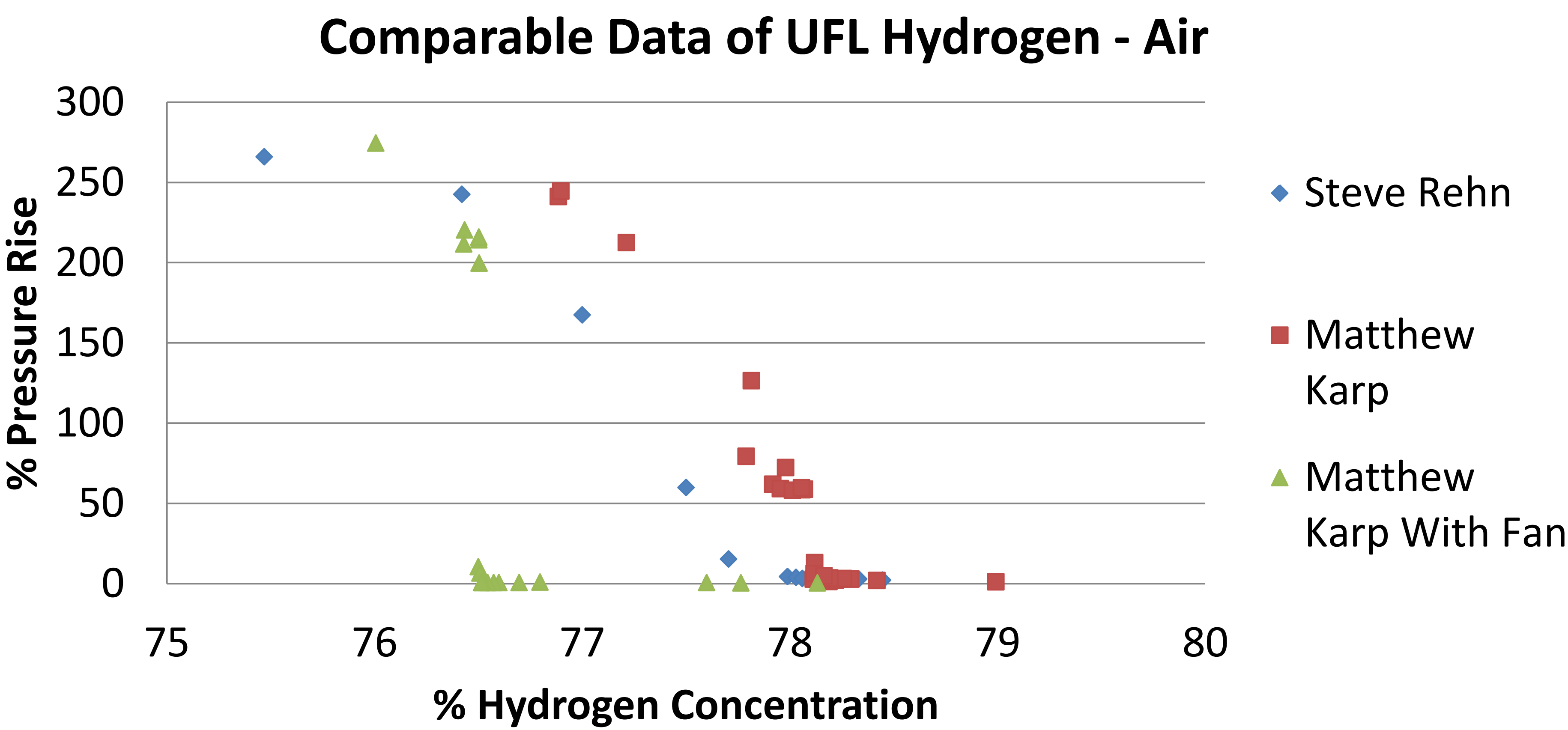
The **LFLs** are determined to be ***4.95±0.40***, **5.35**, and **4.7** % hydrogen concentration for **Matthew Karp with fan**, **Matthew Karp**, and **Steve Rehn** respectively.



Testing validation and data points to determine UFL of hydrogen – air mixture

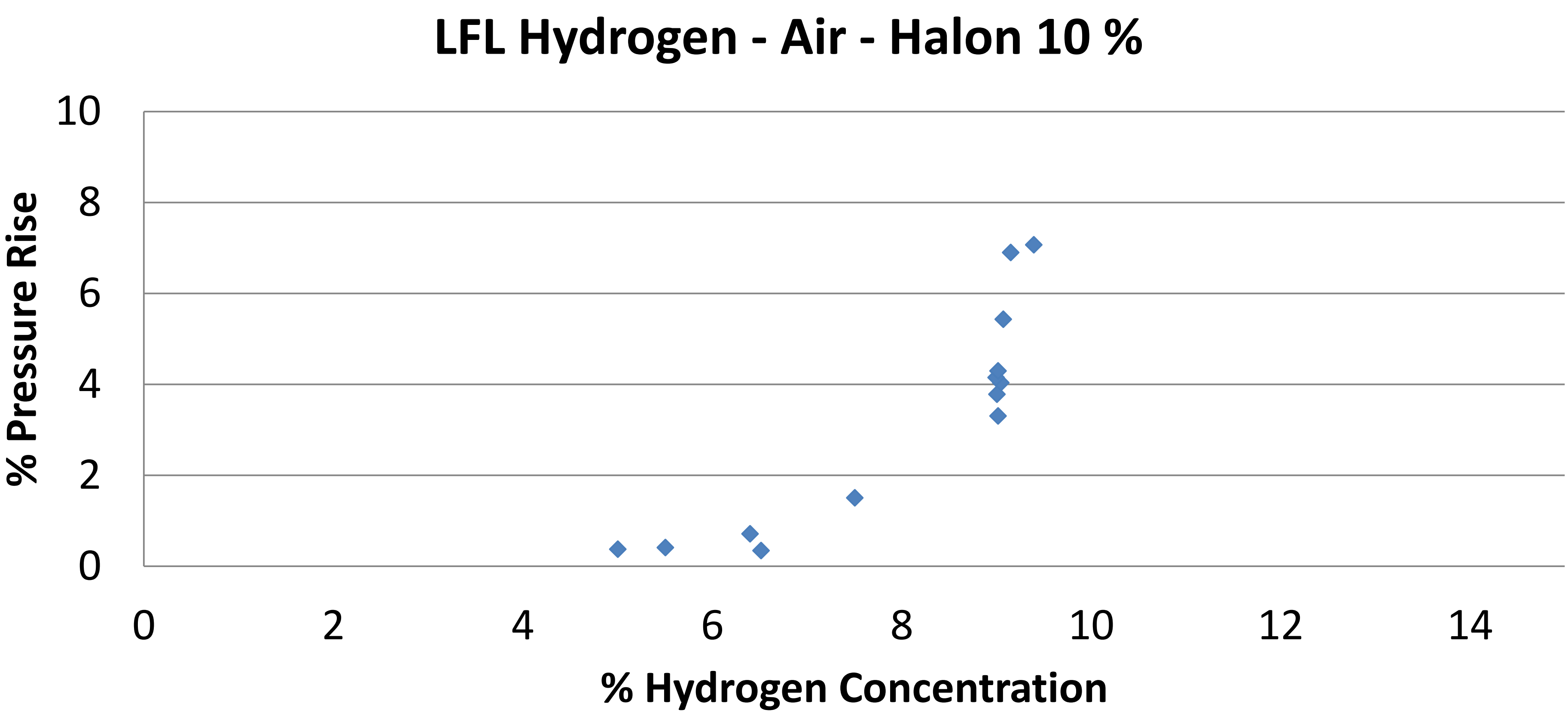
Data points determining the LFL of hydrogen air mixtures are shown below.

The **UFLs** are determined to be ***76.52±0.42***, **78.18**, and **78.87** % hydrogen concentration for **Matthew Karp with fan**, **Matthew Karp**, and **Steve Rehn** respectively.



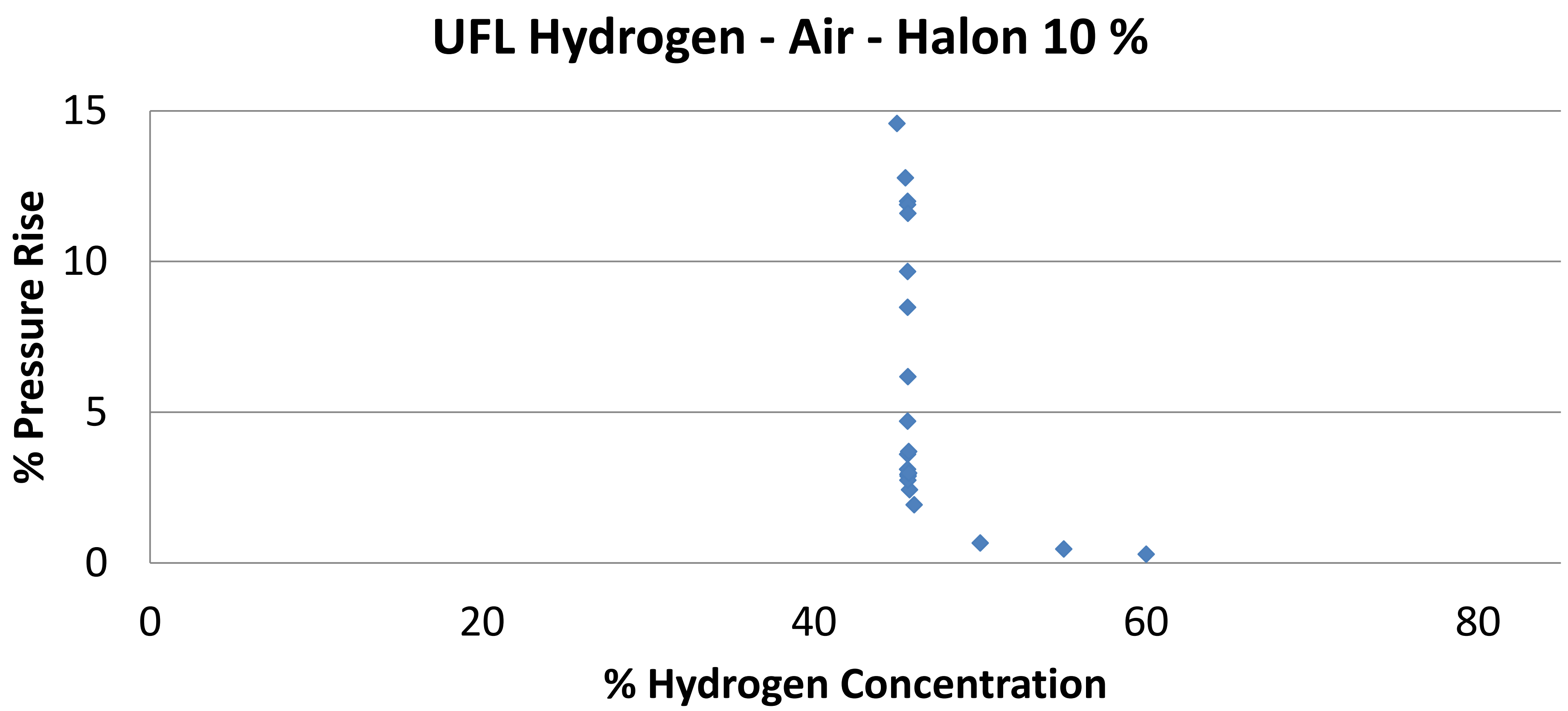
Data points to determine LFL of hydrogen – air – Halon 10 % mixture

13 tests were conducted to determine that the **LFL** of hydrogen – air – Halon 1301 at 10 % is ***9.02±0.51 % hydrogen concentration***



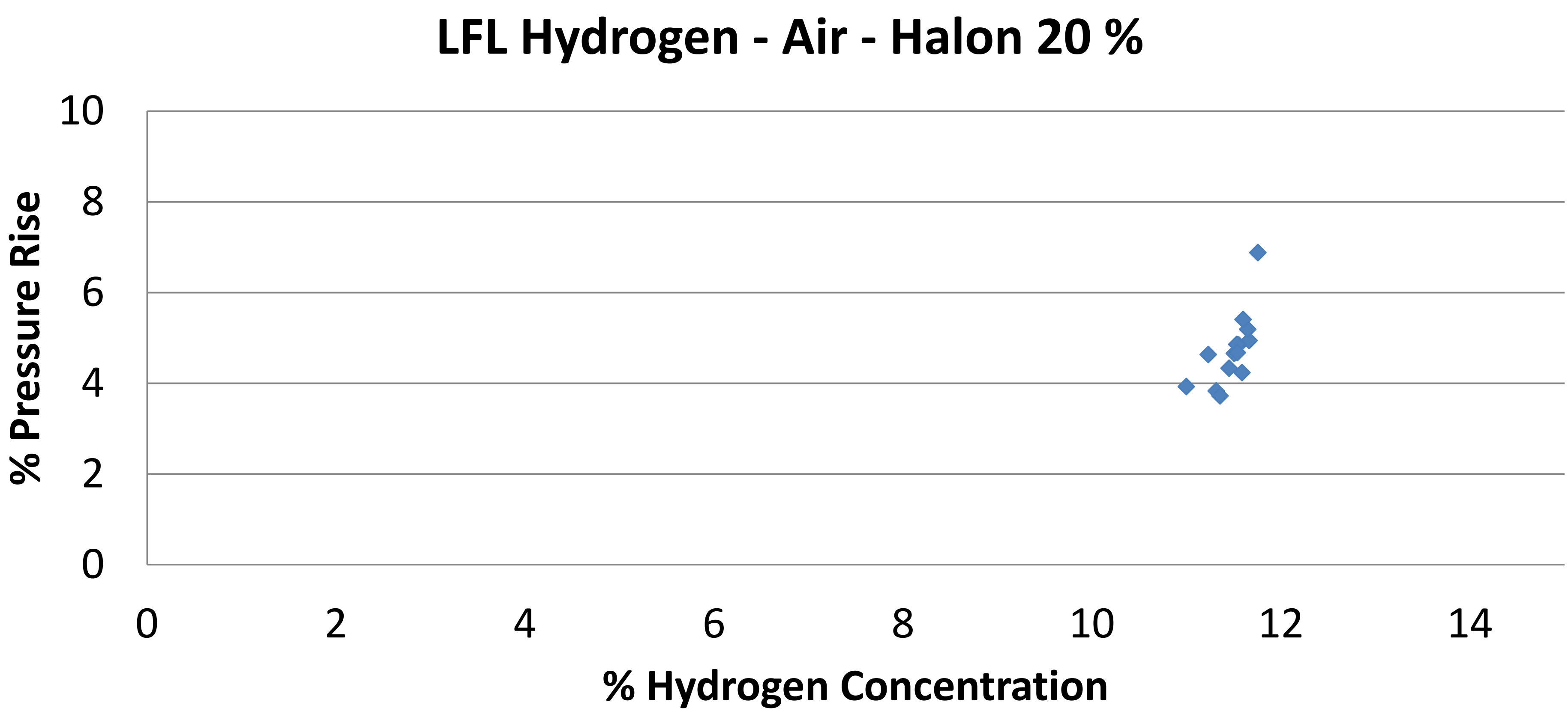
Data points to determine UFL of hydrogen – air – Halon 10 % mixture

21 tests were conducted to determine that the **UFL** of hydrogen – air – Halon 1301 at 10 % is ***9.02±0.51 % hydrogen concentration***



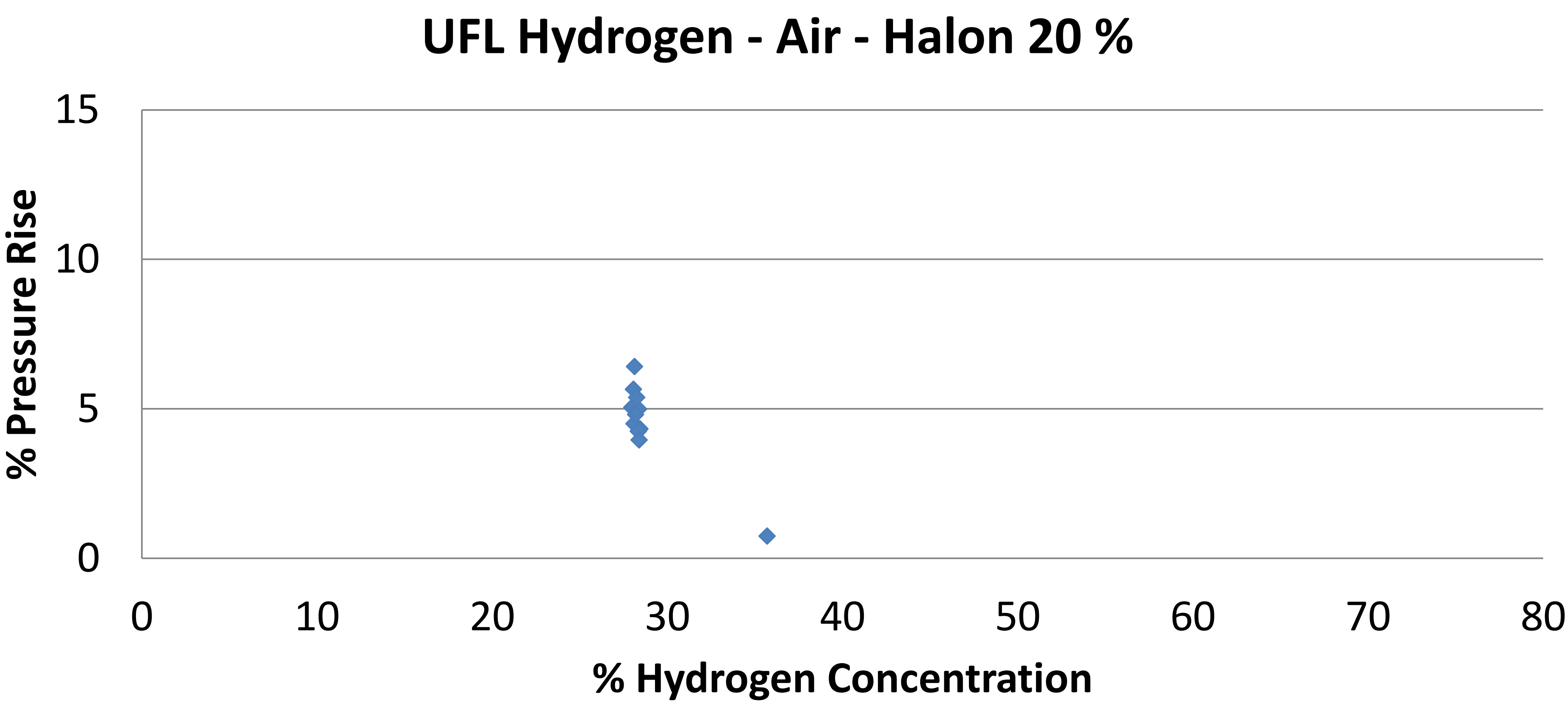
Data points to determine LFL of hydrogen – air – Halon 20 % mixture

14 tests were conducted to determine that the **LFL** of hydrogen – air – Halon 1301 at 20 % is ***11.55±0.48 % hydrogen concentration***



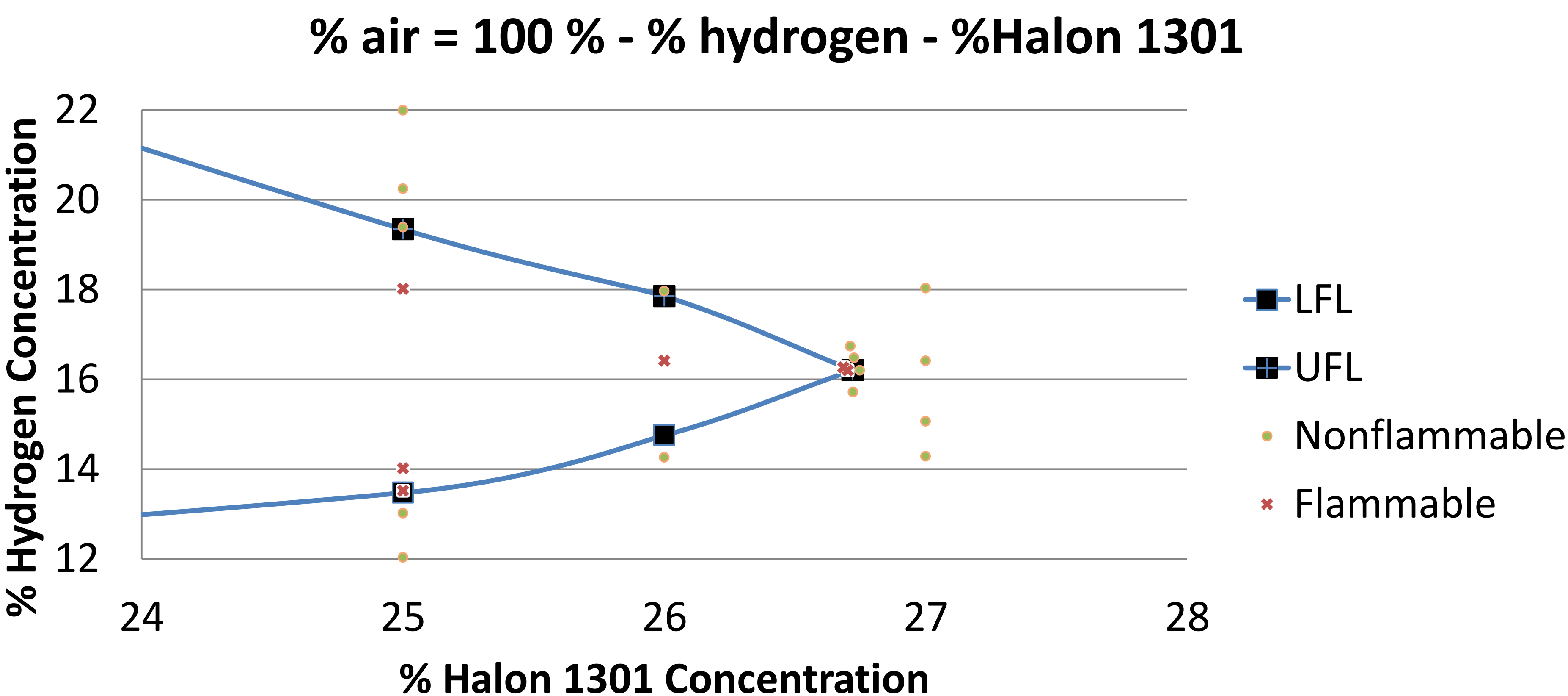
Data points to determine UFL of hydrogen – air – Halon 20 % mixture

16 tests were conducted to determine that the **UFL** of hydrogen – air – Halon 1301 at 20 % is ***28.39±0.47 % hydrogen concentration***



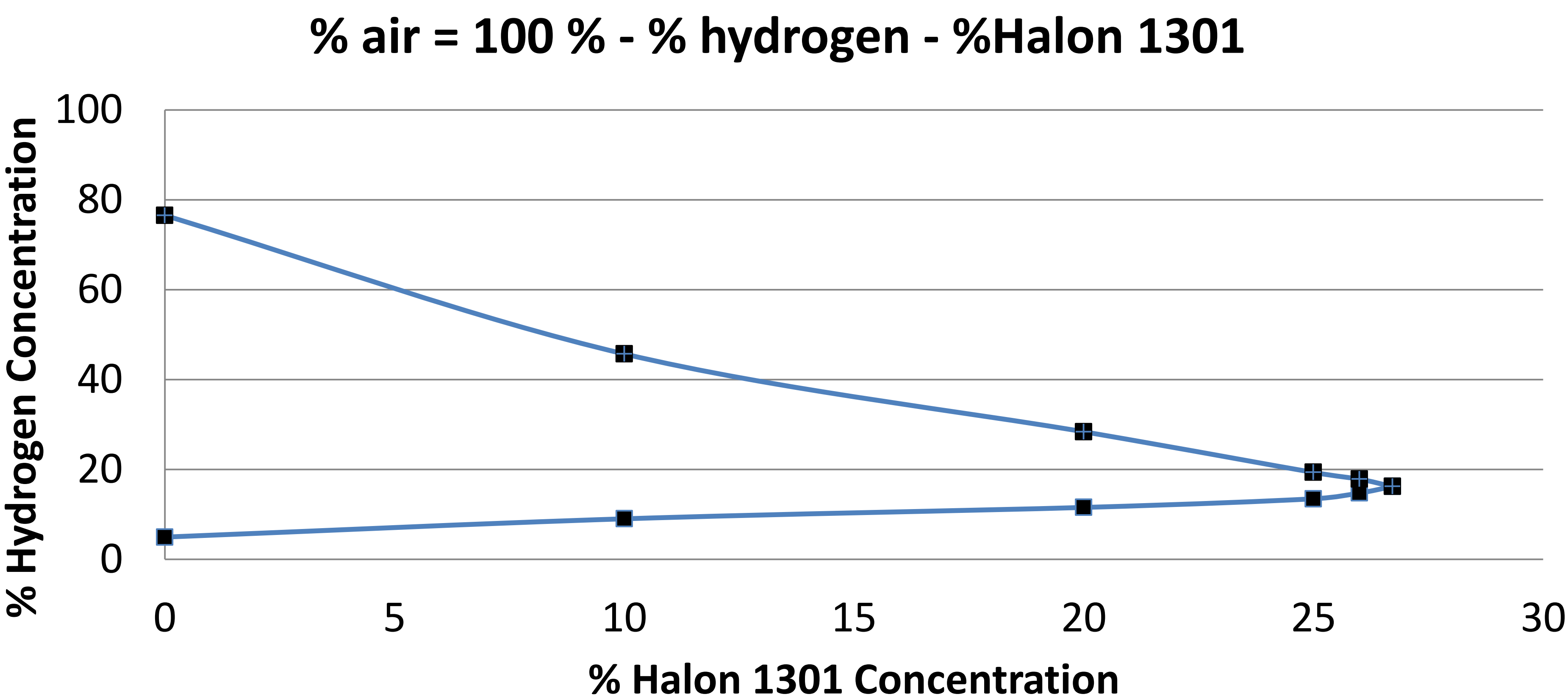
Determining Nose Cap of MIC

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



Limits of flammability of hydrogen – air – Halon 1301 gas mixtures

The limits of flammability are shown to contract as % Halon 1301 concentration increases. Inside the curve is considered flammable while outside is considered nonflammable.



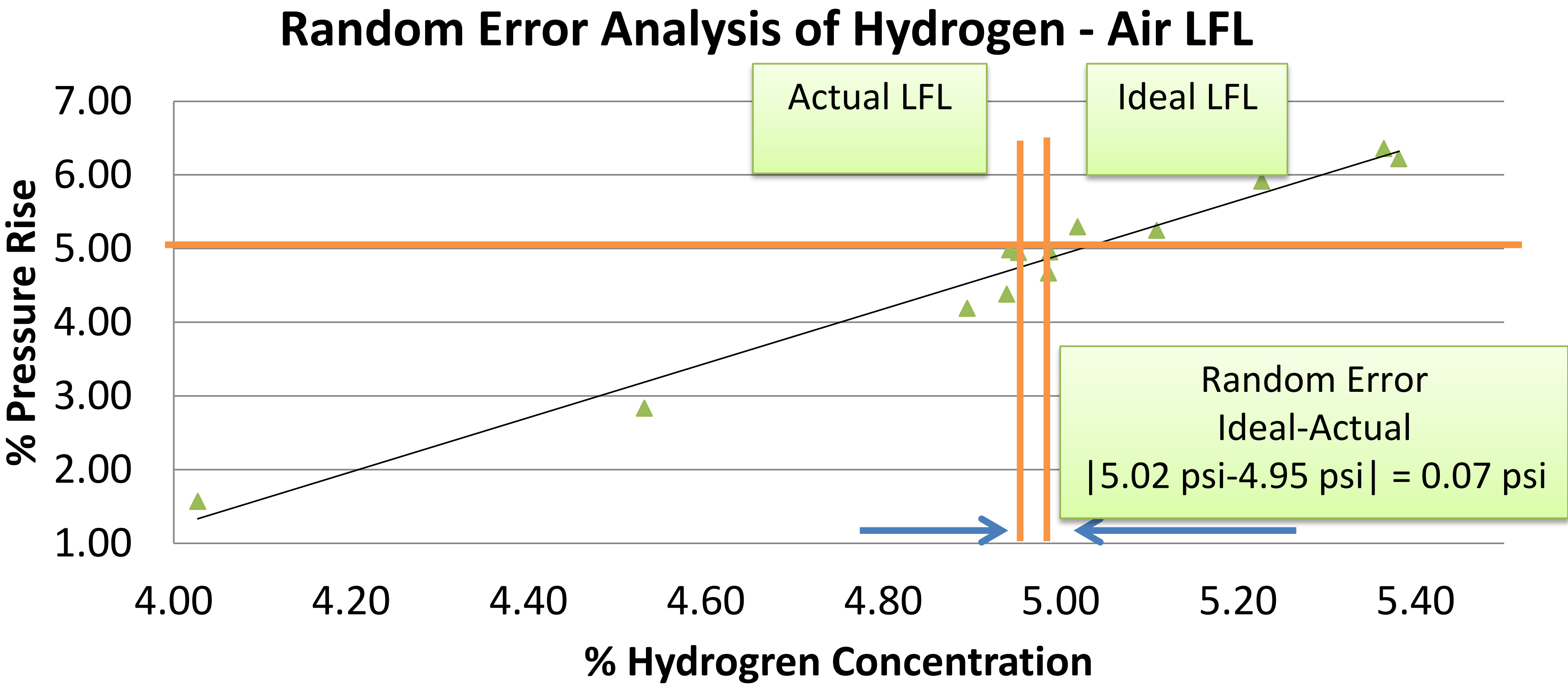
Systematic Error Analysis

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 readings
      - Transducer accuracy ± 0.08 psi

Random Error

Random error is determined by subtracting the best fit line flammability limit (ideal LFL) by the calculated flammability limit (actual LFL).

In this example the random error is calculated to be 0.07 psi



Tester	Air – Hydrogen		Air – Hydrogen – 10% Halon		Air – Hydrogen – 20 % Halon		MIC Halon
	LFL, % hydrogen	UFL, % hydrogen	LFL, % hydrogen	UFL, % hydrogen	LFL, % hydrogen	UFL, % hydrogen	MIC, % hydrogen
Matthew Karp with fan ***(5 % pressure rise)***	***4.95±0.40***	***76.52±0.42***	***9.02±0.51***	***45.70±0.41***	***11.55±0.48***	***28.39±0.47***	***26.72±0.43***
Matthew Karp no fan ***(5 % pressure rise)***	5.35	78.18	-	-	-	-	-
Steve Rehn ***(3 % pressure rise)***	4.7	78.87	-	-	-	-	-
Factory Mutual Research Corporation ***(visual upward flame propagation)***	4	76	5	52	7	31	28
BAM EN 1839 (B) **14 L vessel** ***(5 % pressure rise)***	4.2	77	-	-	-	-	-
Herzberg & Cashdollar **20 L vessel** ***(3 % pressure rise)***	5 ± 0.5	76.8 ± 0.2	-	-	-	-	-

Conclusion

- Over 200 tests have been conducted in determination of current figures.
- The LFL and UFL of hydrogen – air – Halon 1301 mixtures were experimentally determined.
- Reproducible data is being 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.

Future Work

Future experiments will be conducted to determine:

- The MIC of Halon 1301 in hydrogen – air mixtures
- The LFL and UFL of lithium ion battery gas – air – Halon 1301 mixtures
- The MIC of Halon 1301 in lithium ion battery gas – air – Halon 1301 mixtures