Flammability Limits of Hydrogen at Sub-Atmospheric Pressures and Reduced Oxygen Concentrations

Presented to: The Seventh Triennial International Fire & Cabin Safety Research Conference
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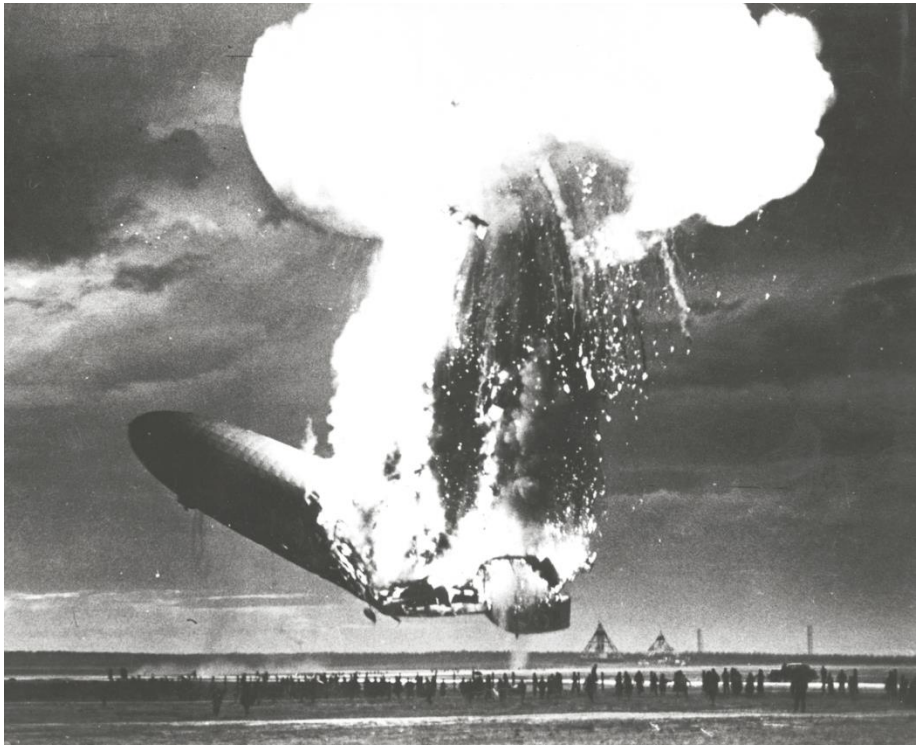
Date: 12/05/2013

Introduction

- **There is increasing pressure on the aviation industry to improve efficiency and reduce emissions**
- **One method would be to replace the Auxiliary Power Unit (APU) with hydrogen fuel cells**
- **In addition, fuel cells could reduce noise, produce water, provide emergency power, and produce oxygen-depleted air to fill the empty space in fuel tanks**

Background



Hindenburg disaster, 1937

U.S. Navy File Photo

Boeing Fuel Cell Demonstrator, 2008

Photo Credit: Adambro, Creative Commons

Hydrogen Properties

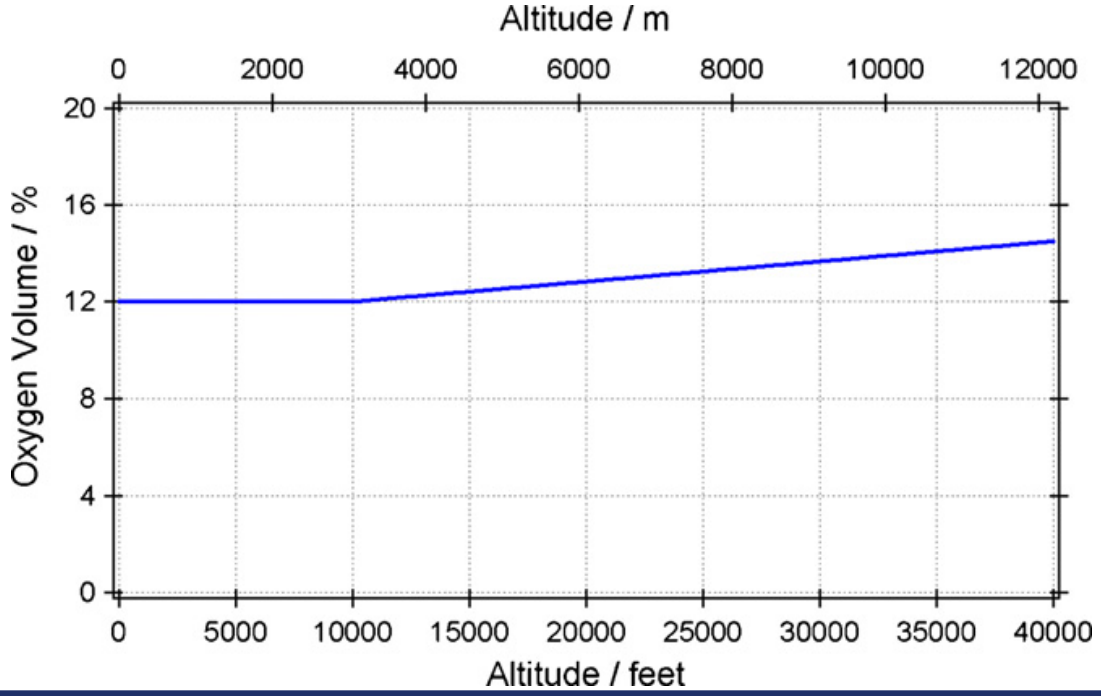
- **Hydrogen has very wide flammability limits (~5-75% at sea level)**
- **Very low ignition energy needed (<0.1mJ)**
- **In a closed container, explosion pressure rises up to 8 times initial pressure in as little as 10ms**
- **Adiabatic flame temperature of 4010°F (2210°C)**

Objective

- **Test flammability of hydrogen in air at atmospheric and sub-atmospheric pressures**
- **Pressures replicating elevations of 0, 15,000, 30,000, and 40,000 feet (14.7, 8.29, 4.36, and 2.71 PSI, respectively)**
- **Find flammability limits and verify with previous data**
- **Test flammability properties and in oxygen-depleted air at these pressures (added nitrogen)**
- **Find the limiting oxygen concentration**

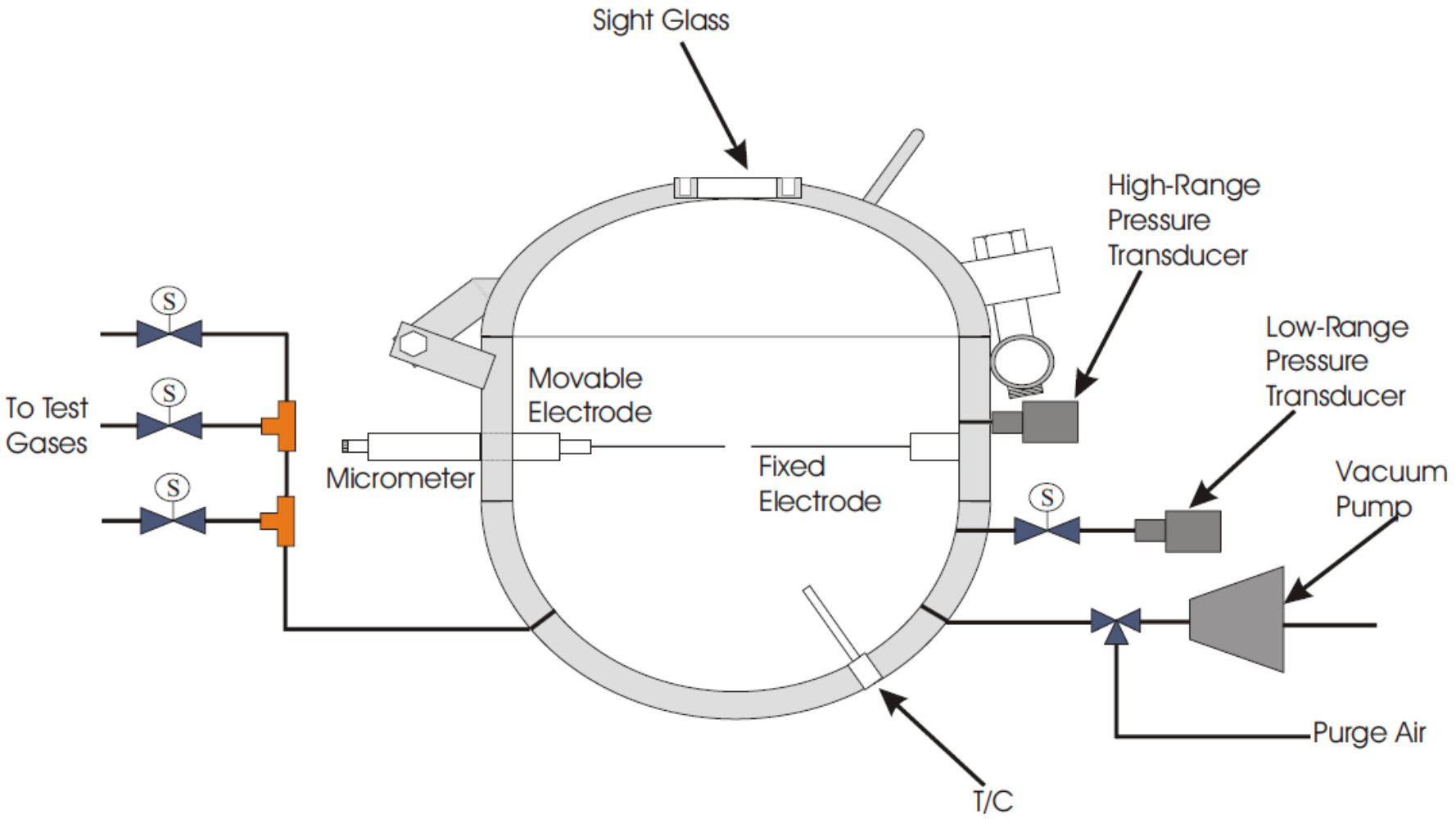
Concept

- **Nitrogen can be added to air to lower the oxygen concentration, effectively inerting the H_2-air mixture**
- **Similar to inerting the empty space in jet fuel tank**

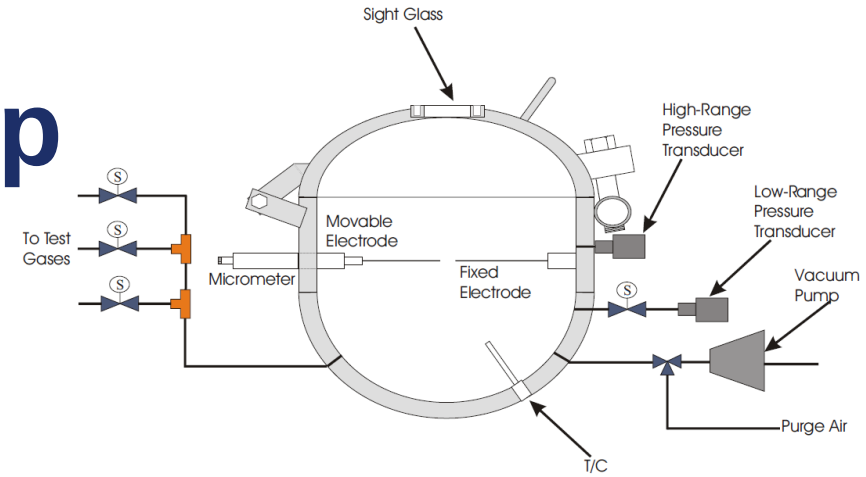


Allowable oxygen concentration vs. altitude according to AC 25-981-2A

Experimental Setup

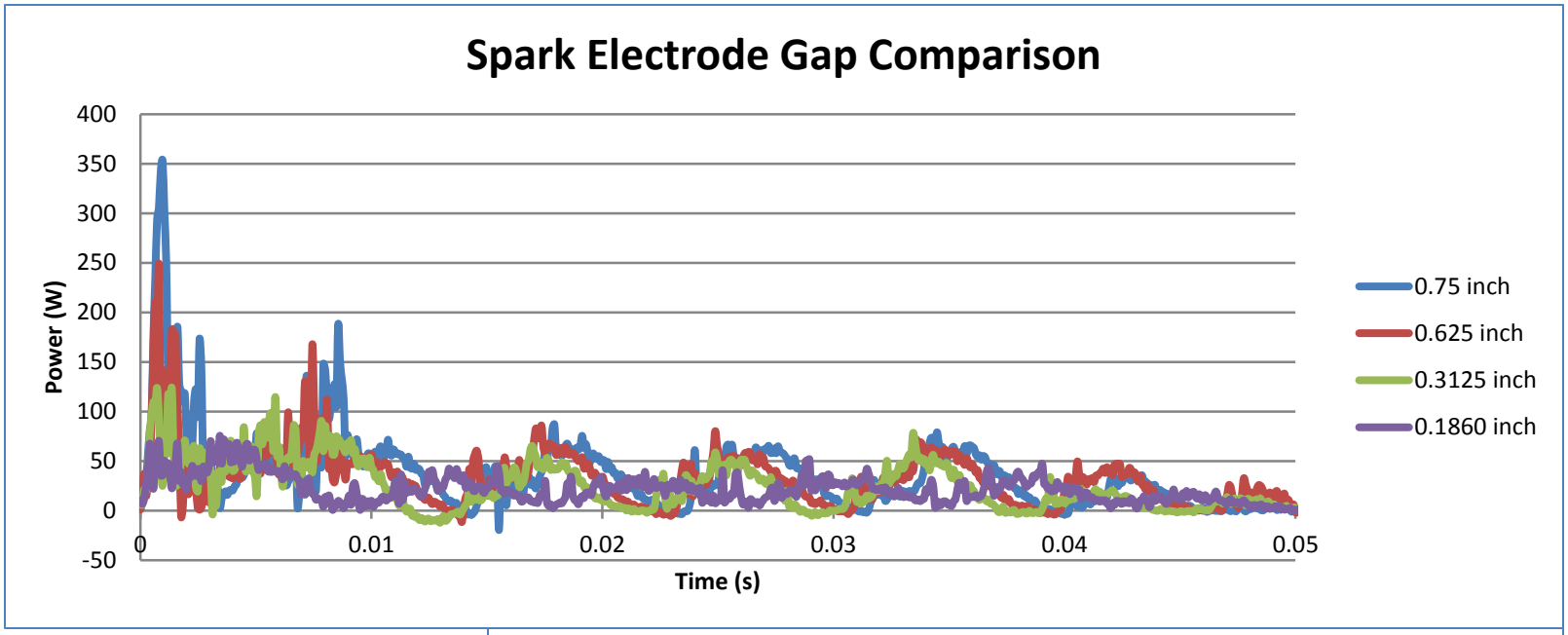


Experimental Setup

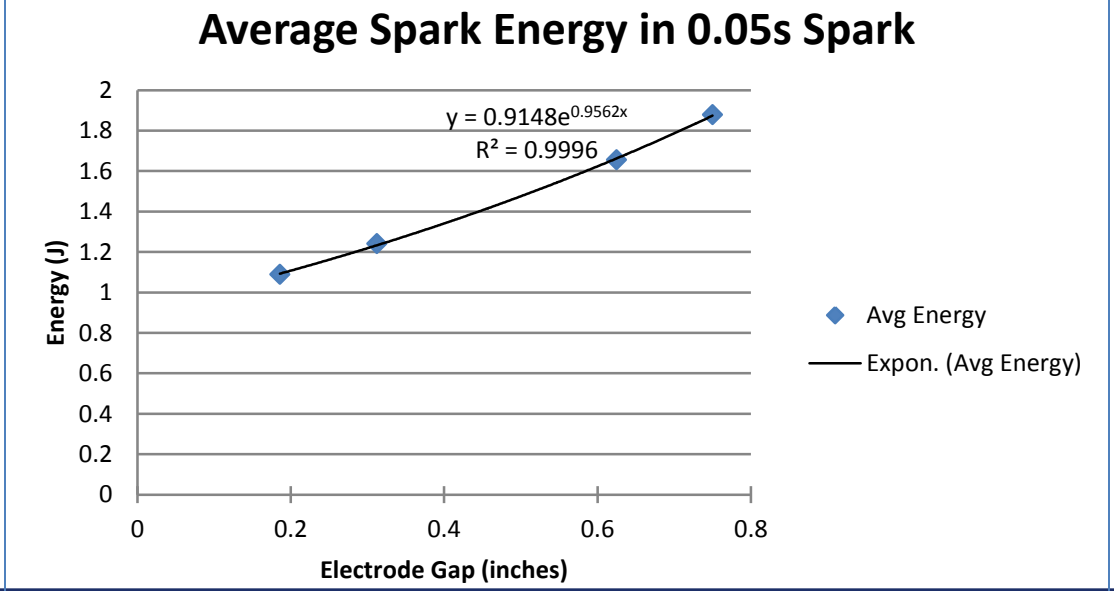


- **20L, ½” thick steel chamber**
- **300 PSI maximum pressure**
- **Chamber evacuated, then filled by partial pressures**
- **Can mix hydrogen, nitrogen, and air at any ratio**
- **Initial pressure varied from 2.71 to 14.7 PSI**
- **Initial temperature 72°F (22°C)**
- **Ignited with 15,000V, 30mA continuous spark, 0.5s duration**
- **Considered flammable if pressure rise 3% over initial pressure**

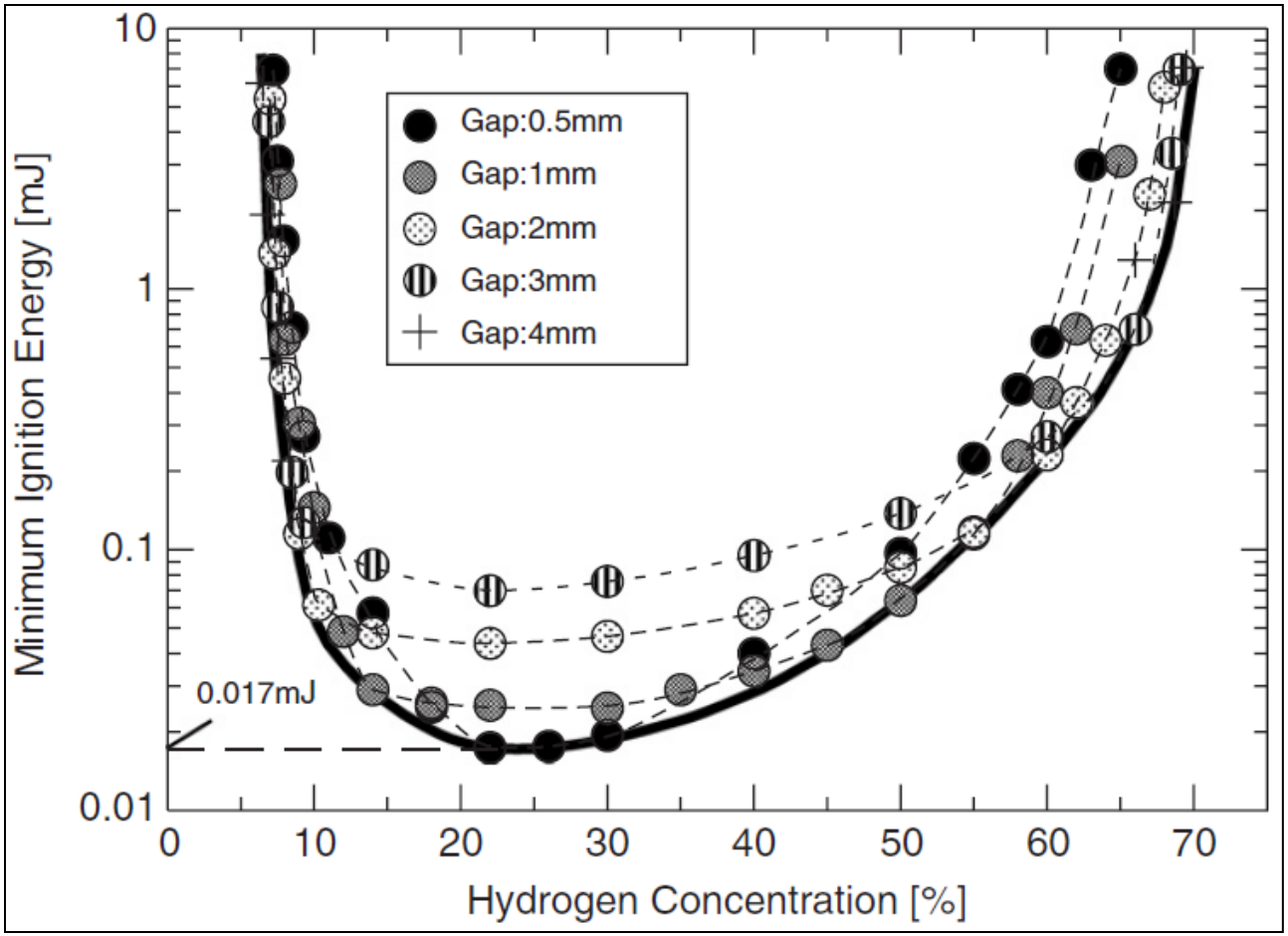
Experimental Setup



Gap (in.)	Avg. Energy (J)
0.186	1.09
0.3125	1.24
0.625	1.65
0.75	1.88



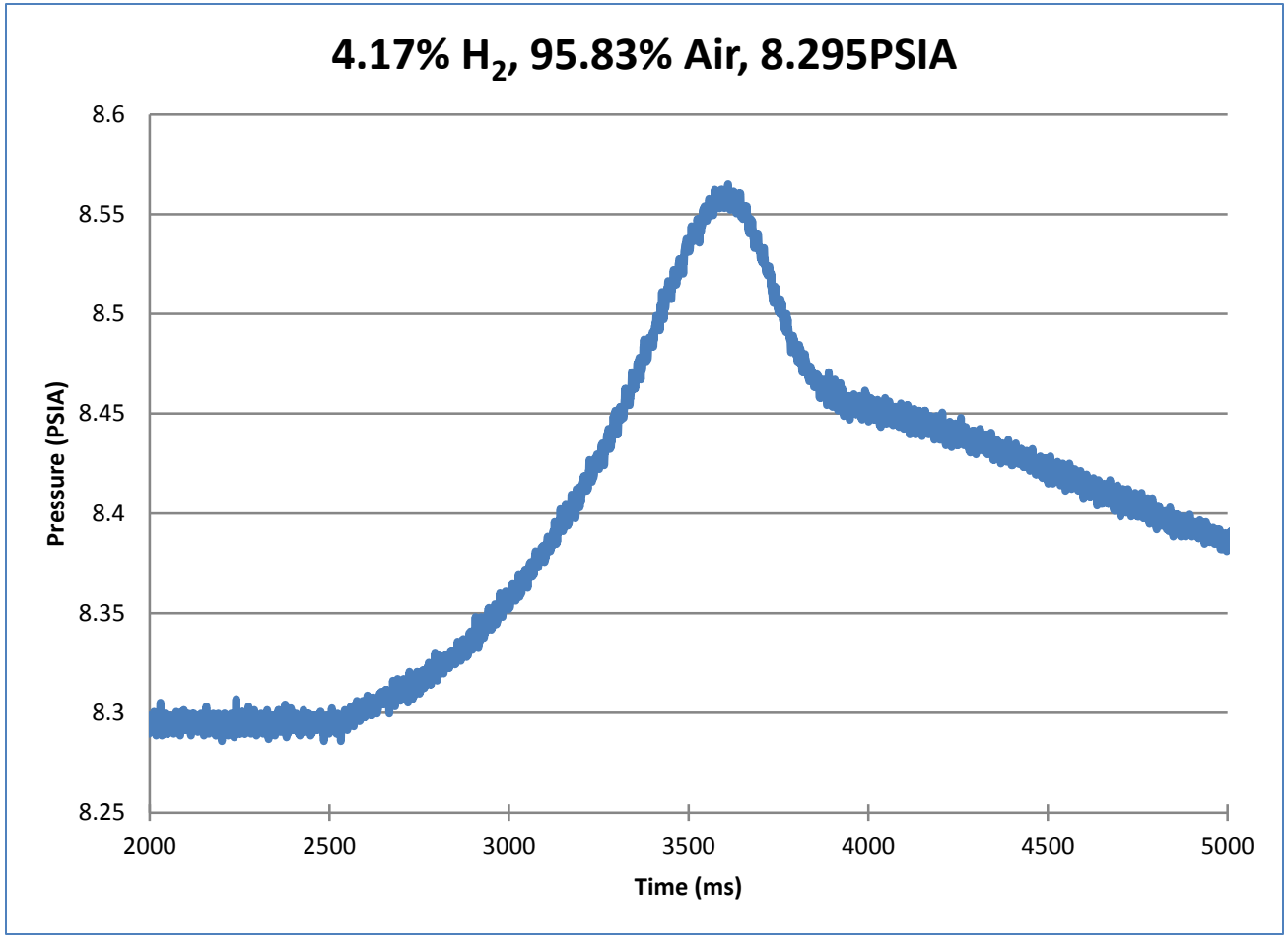
From Literature



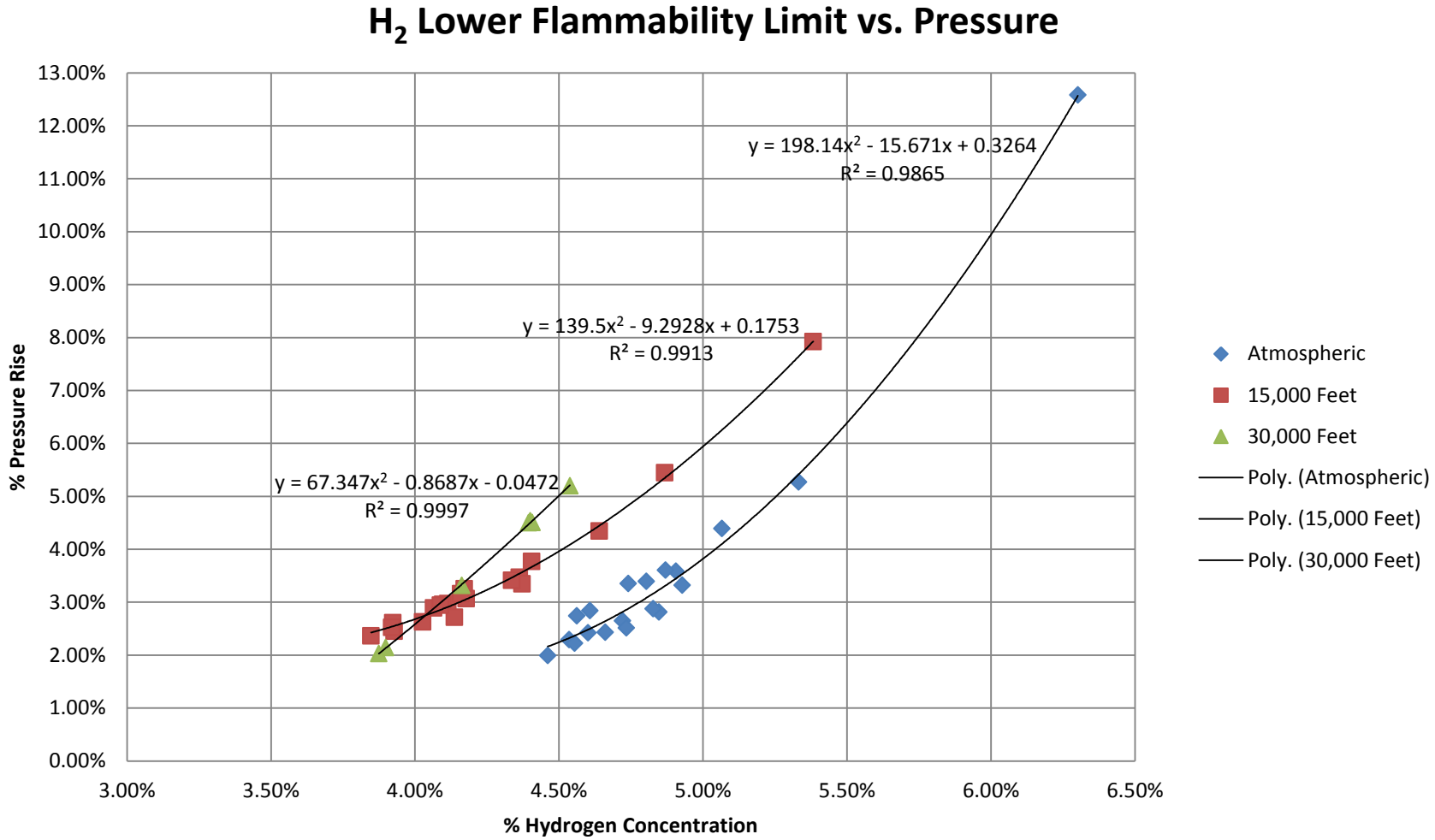
From *Minimum ignition energy of hydrogen–air mixture: Effects of humidity and spark duration,* Ryo Ono, et. al, University of Tokyo, 2007.

- Flammability limits are wider with larger spark gap

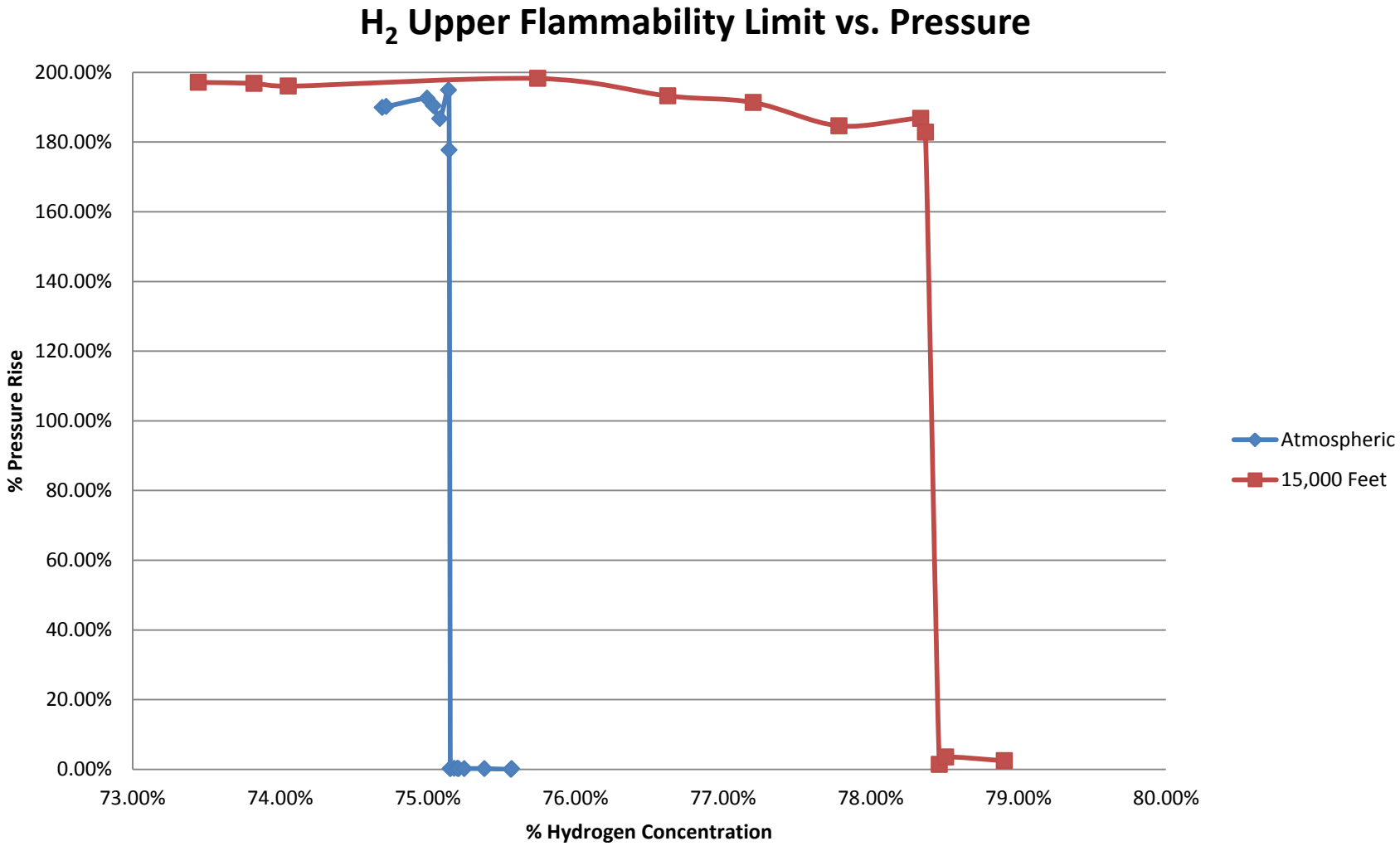
Example of Single Test Pressure data



- Pressure rise of 3.25%



- Atmospheric LFL (14.7PSIA): 4.78%
- 15,000 Feet LFL (8.29PSIA): 4.15%
- 30,000 Feet LFL (4.36PSIA): 4.09%



- Atmospheric UFL (14.7PSIA): 75.14%
- 15,000 Feet UFL (8.29PSIA): 78.37%

Inerting with Nitrogen in Literature

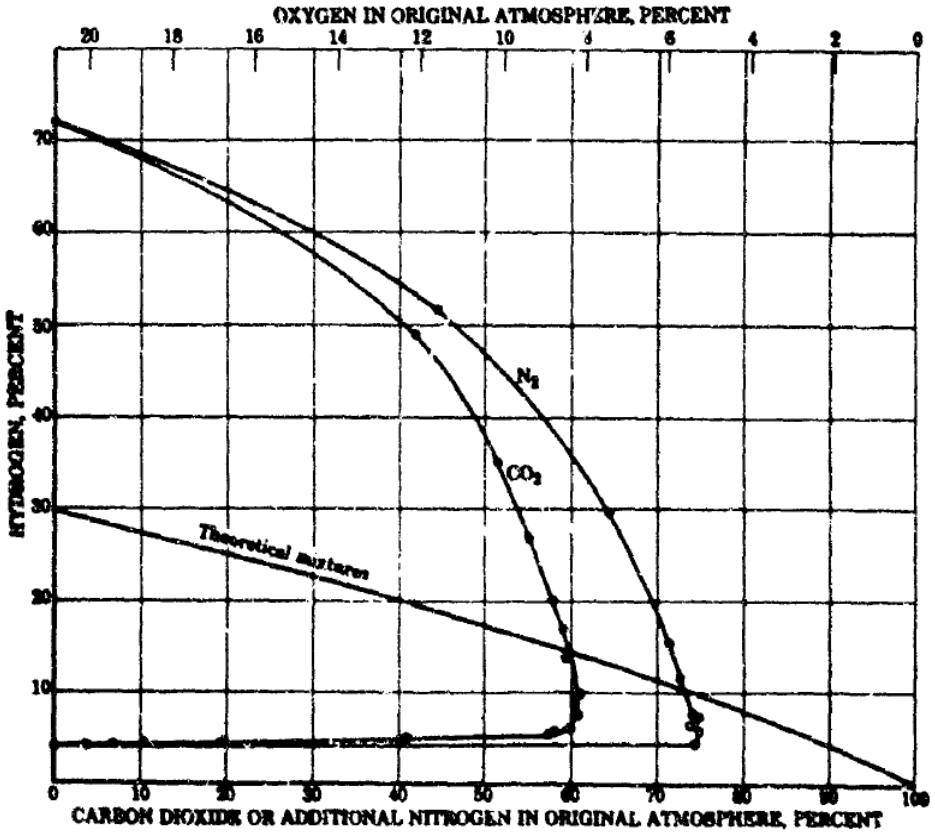
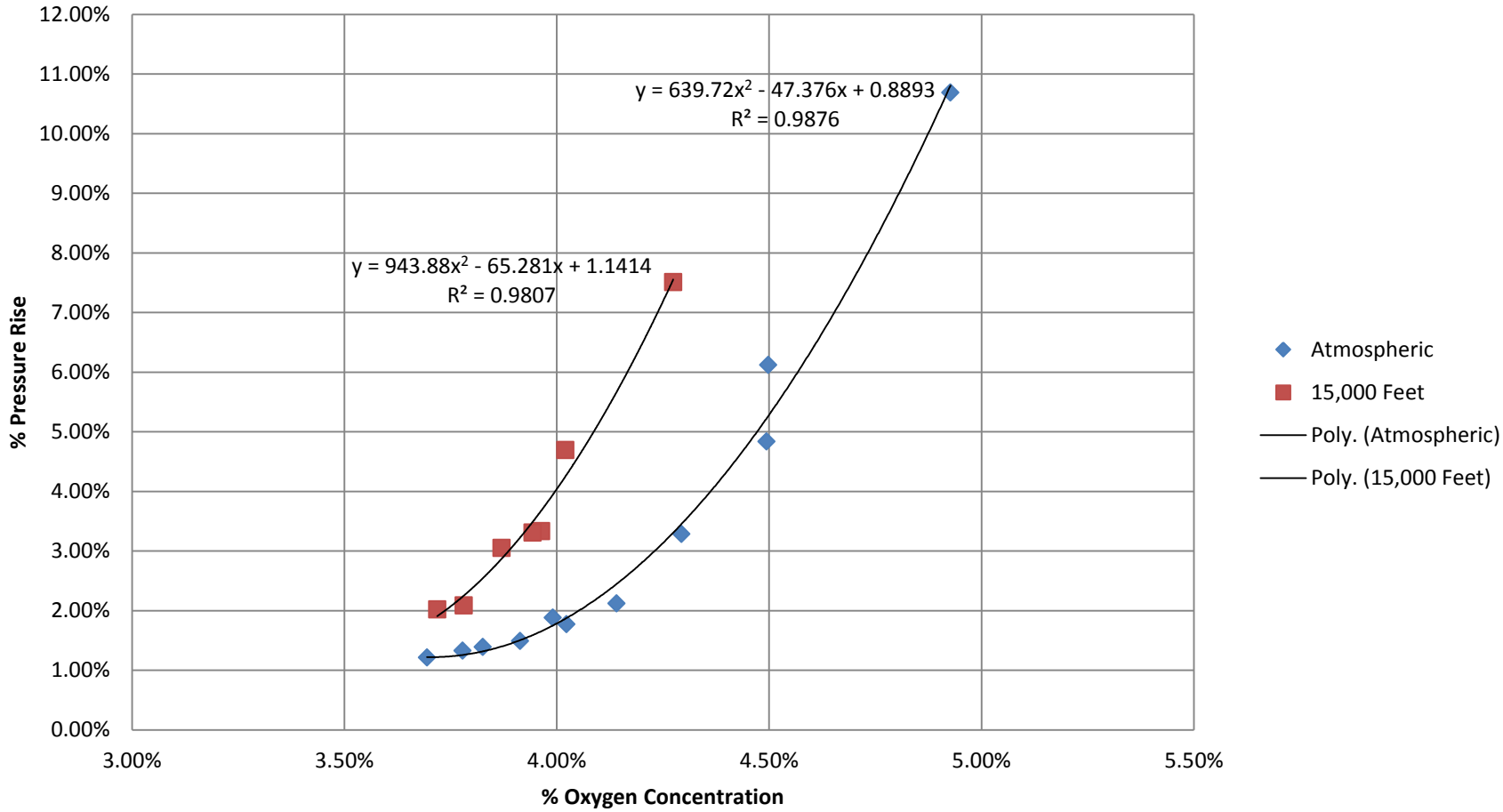


FIGURE 7.—Limits of Flammability of Hydrogen in Air and Carbon Dioxide or Nitrogen.

From *Limits of Flammability of Gases and Vapors,* H. F. Coward and G. W. Jones, Bureau of Mines, 1952.

- Tested in a 6 ft by 2 in diameter tube at atmospheric pressure
- Flame did not propagate below 4.9% oxygen concentration

Limiting Oxygen Concentration vs. Pressure



- Tests done with 6-7% hydrogen
- Atmospheric Limiting Oxygen Concentration (14.7PSIA): 4.23%
- 15,000 Feet Limiting Oxygen Concentration (8.29PSIA): 3.89%

Comparison

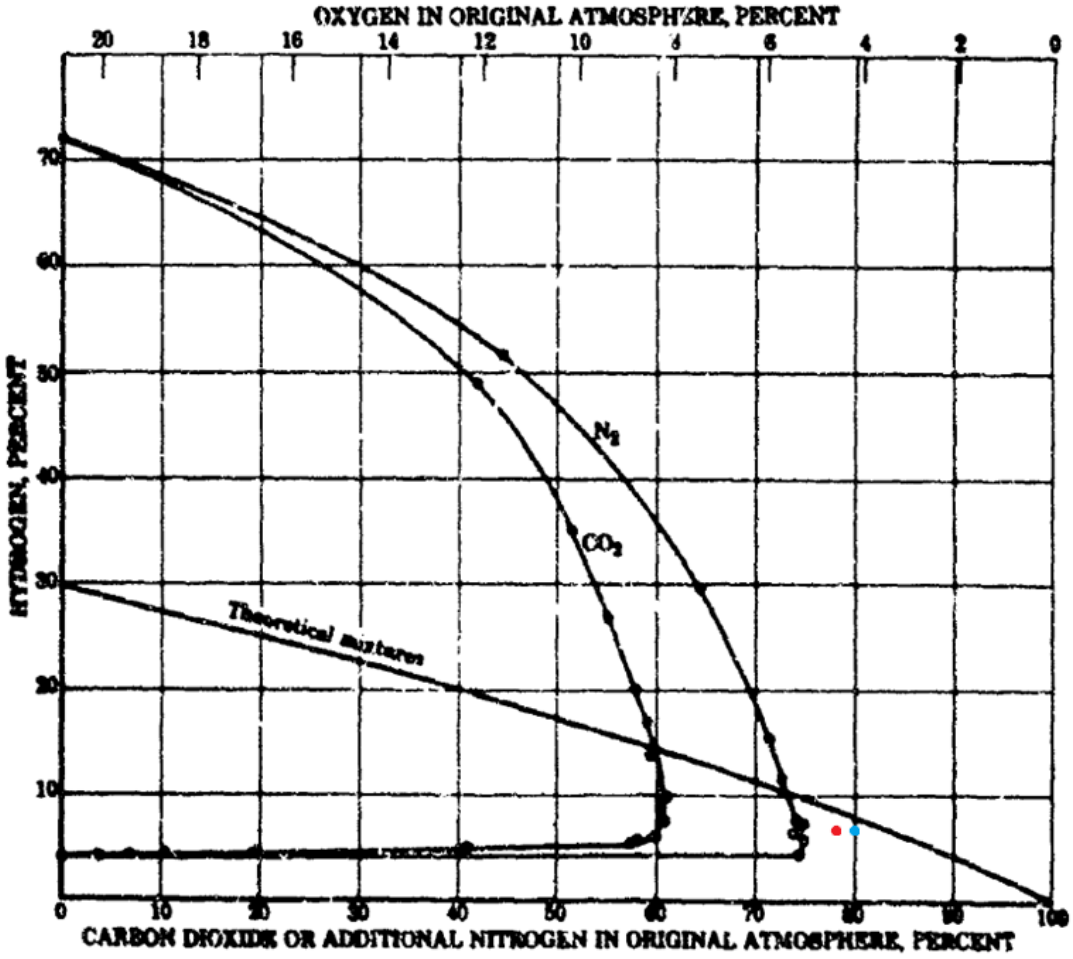


FIGURE 7.—Limits of Flammability of Hydrogen in Air and Carbon Dioxide or Nitrogen.

- Atmospheric
- 15,000 Feet

Conclusion and Future Work

- **H_2 flammability limits widen at high altitude**
- **H_2 requires less O_2 to ignite at high altitudes, so more N_2 is required to inert it**
- **More testing is still required for flammability limits at 30,000 and 40,000 feet**
- **Limiting O_2 concentration needs to be found for 30,000 and 40,000 feet**
- **More testing in O_2 depleted air at all altitudes to construct complete flammability limit curves**