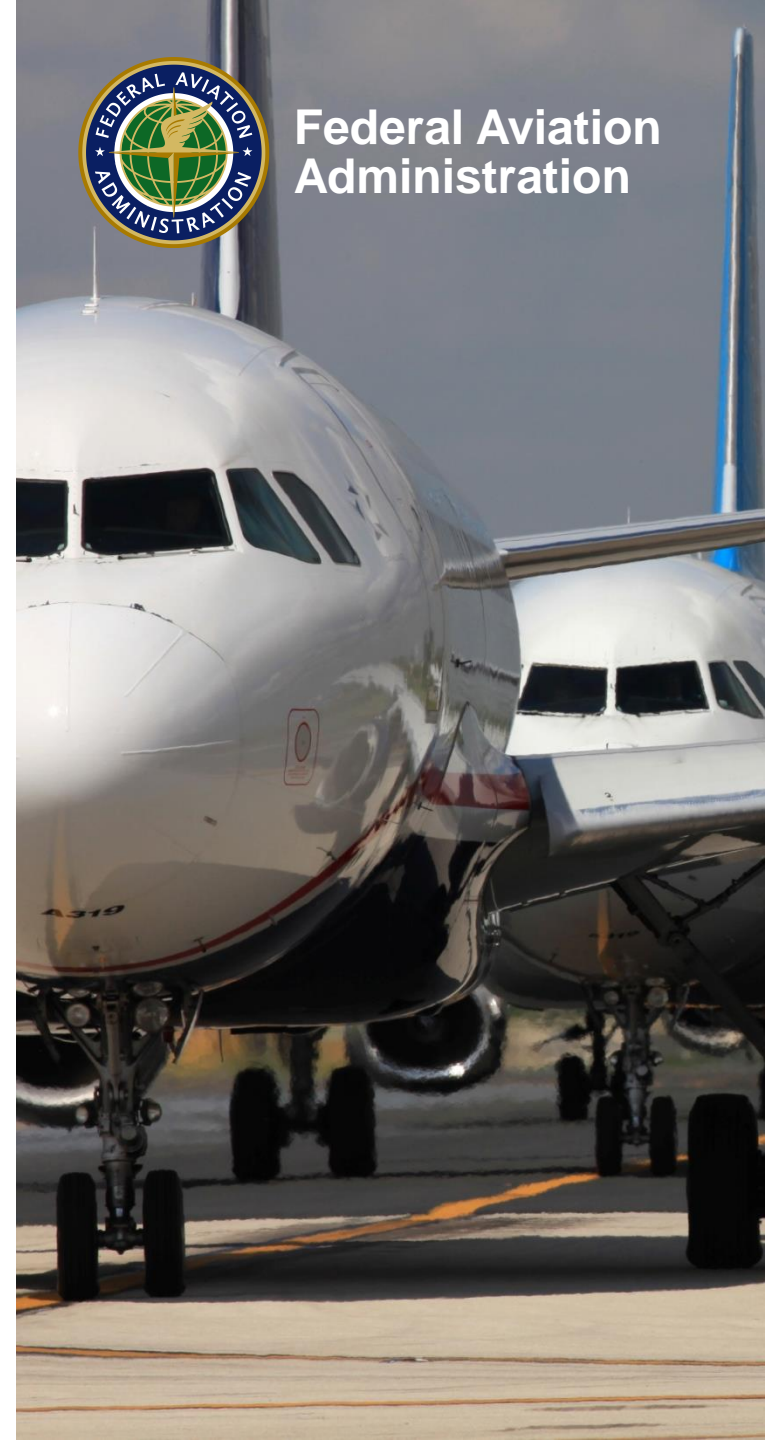


Flammability Limits of Hydrogen at Sub-Atmospheric Pressures and Reduced Oxygen Concentrations

Presented to: SAE Hydrogen Fuel Cell Working Group Meeting
By: Steven Rehn
Date: 3/25/2014



Federal Aviation
Administration



Hydrogen Properties

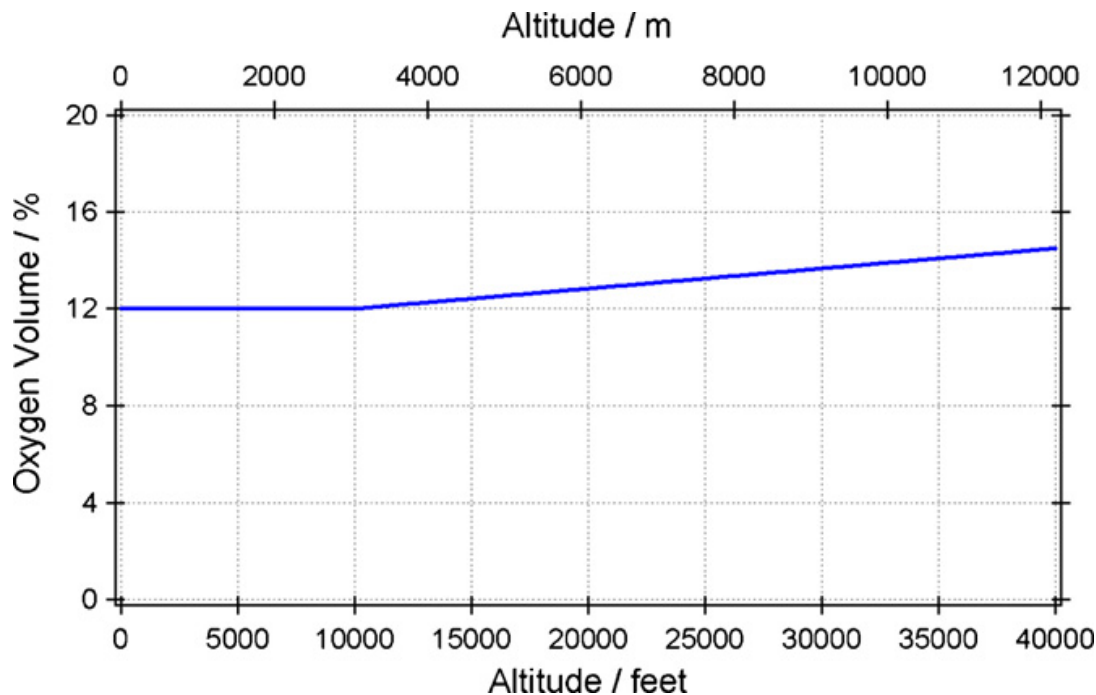
- **Hydrogen has very wide flammability limits (~5-75% at sea level)**
- **Very low ignition energy needed (<0.1mJ)**
- **In a closed container, explosion pressure rises up to 8 times initial pressure in as little as 10ms**
- **Adiabatic flame temperature of 4010°F (2210°C)**

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**

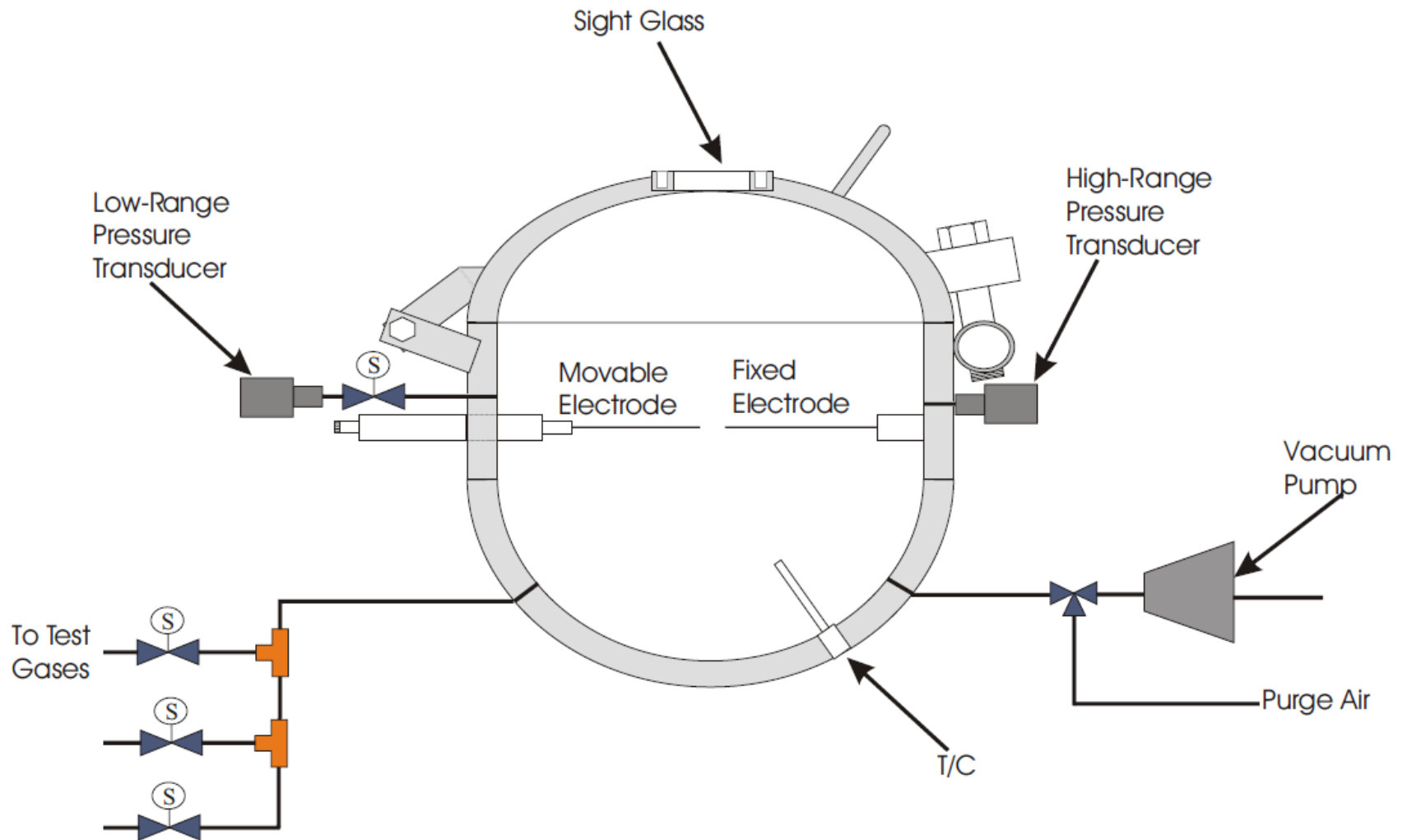
Concept

- Nitrogen can be added to air to lower the oxygen concentration, effectively inerting the H₂-air mixture
- Similar to inerting the empty space in jet fuel tank

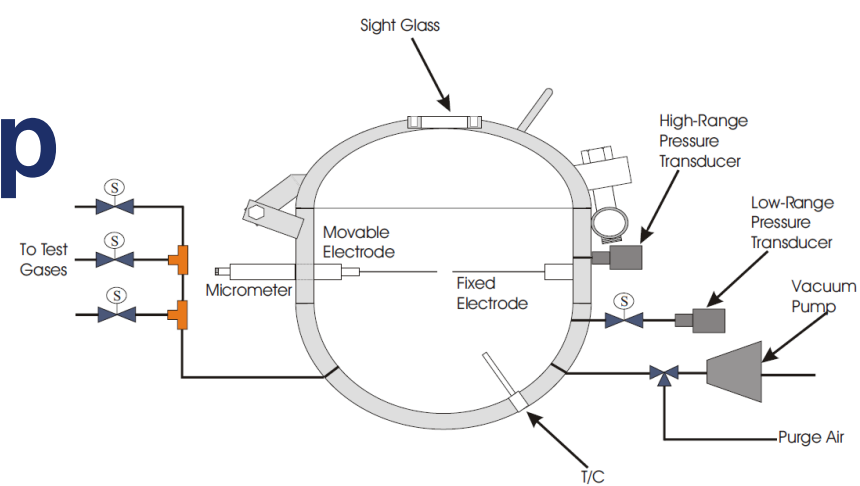


Allowable oxygen concentration vs. altitude according to AC 25-981-2A

Experimental Setup

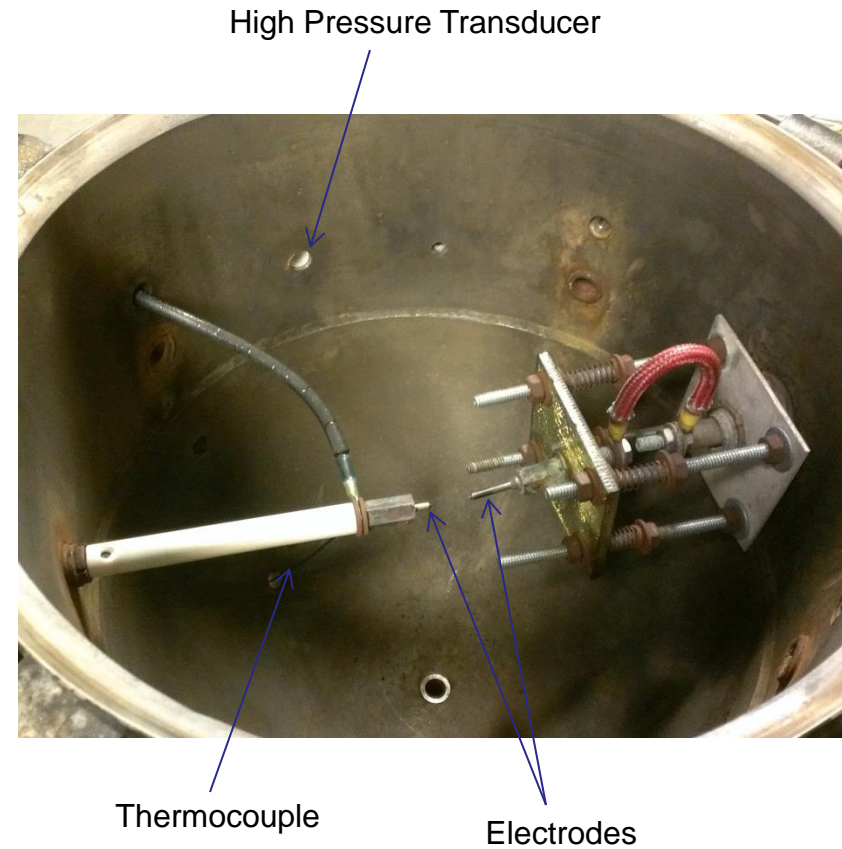
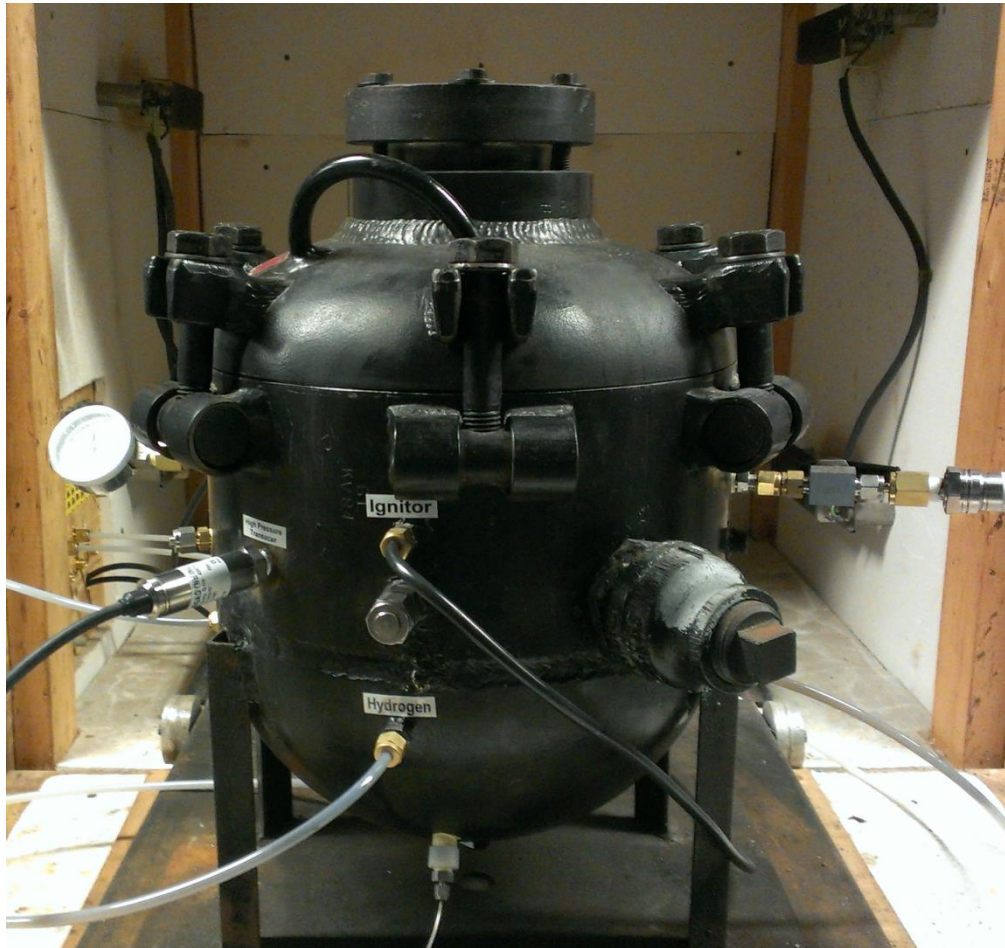


Experimental Setup

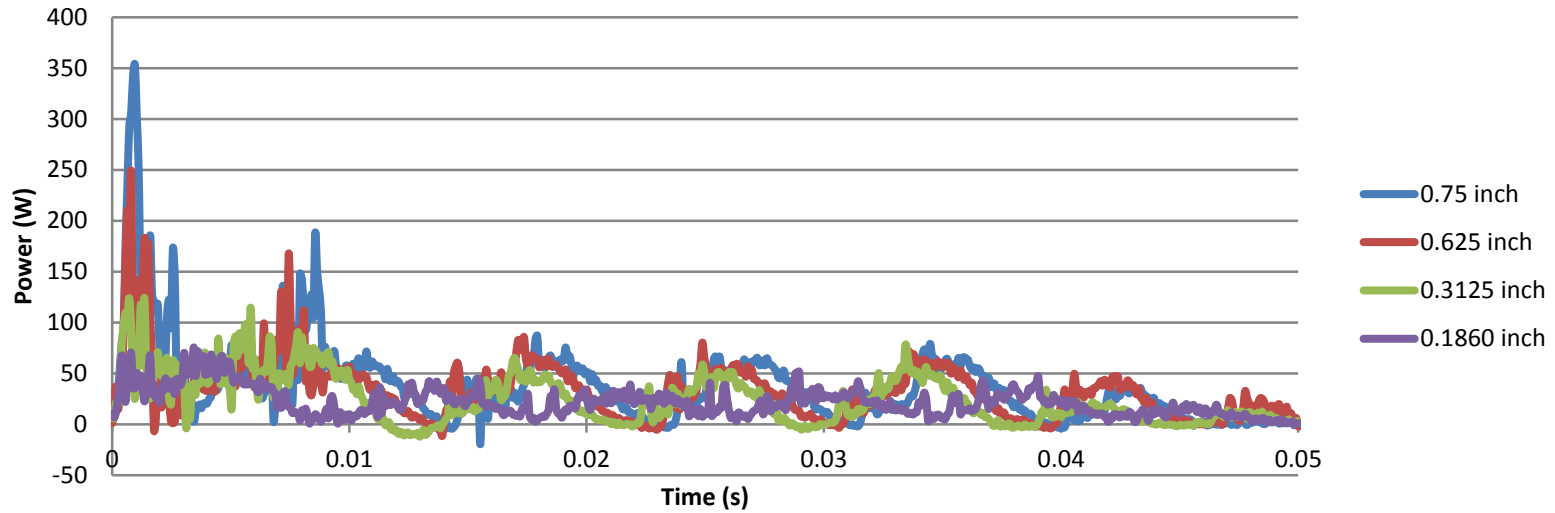


- **20L, 1/2" thick steel chamber**
- **300 PSI maximum pressure**
- **Chamber evacuated, then filled by partial pressures**
- **Can mix hydrogen, nitrogen, and air at any ratio**
- **Initial pressure varied from 2.71 to 14.7 PSI**
- **Initial temperature 72°F (22°C)**
- **Ignited with 15,000V, 30mA continuous spark, 0.5s duration**
- **Considered flammable if pressure rise 3% over initial pressure**

Experimental Setup

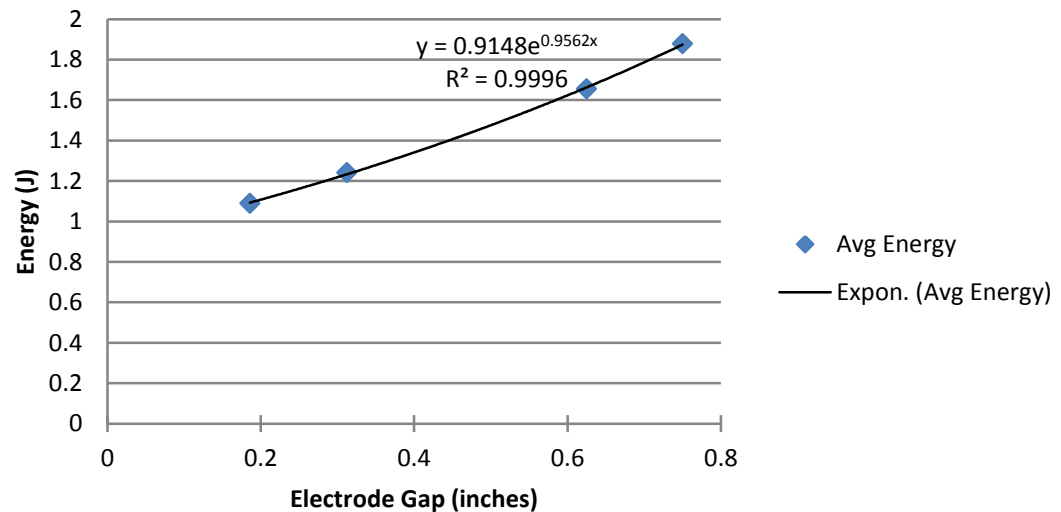


Spark Electrode Gap Comparison

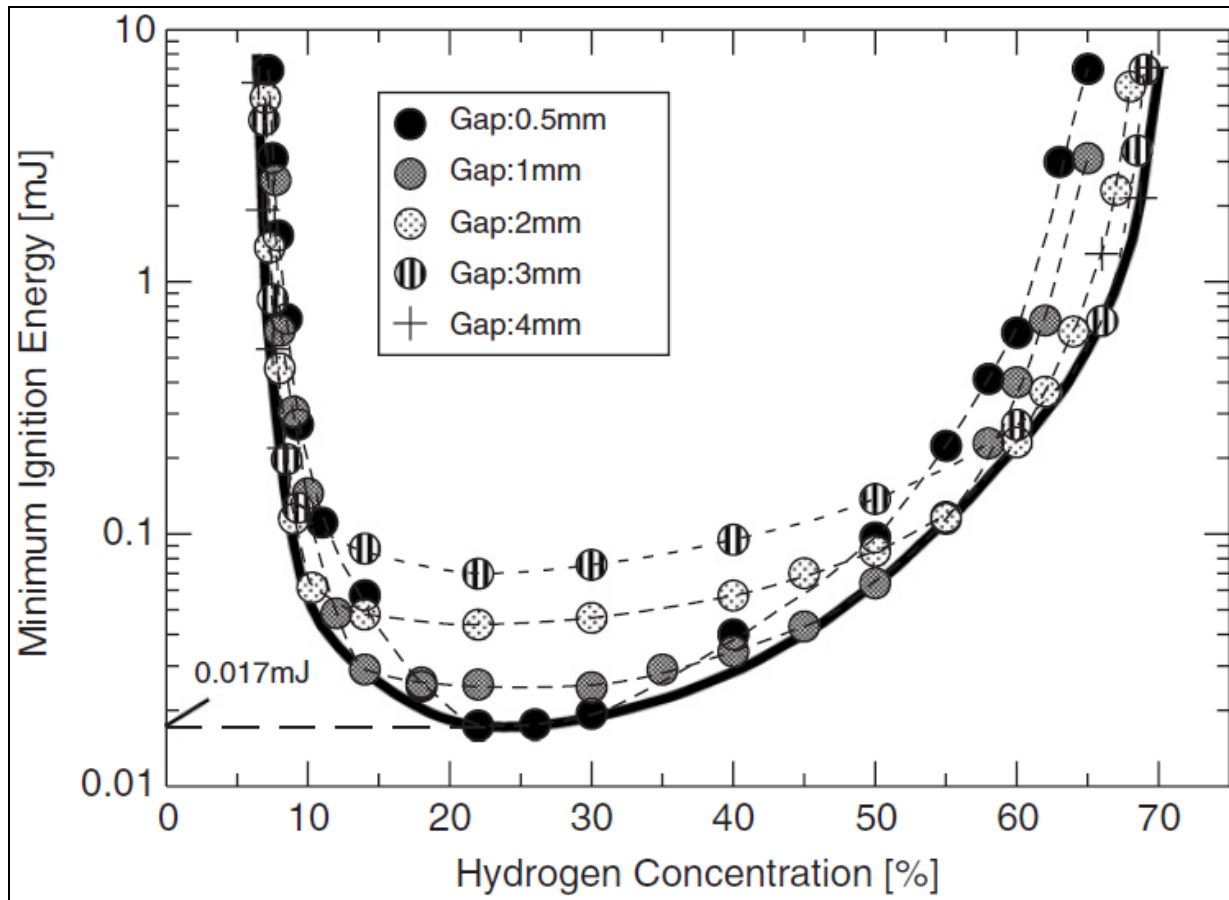


Gap (in.)	Avg. Energy (J)
0.186	1.09
0.3125	1.24
0.625	1.65
0.75	1.88

Average Spark Energy in 0.05s Spark



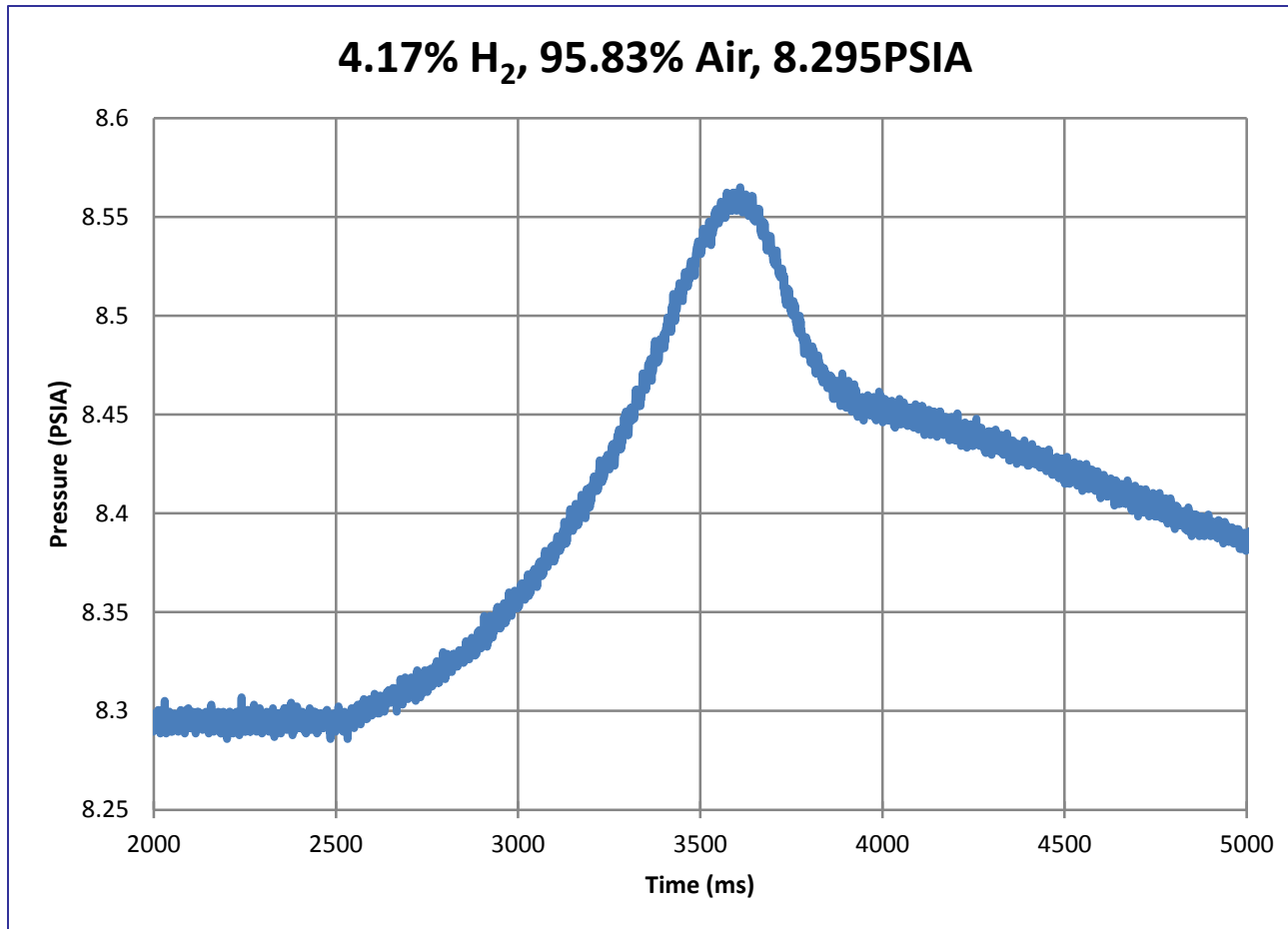
From Literature



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

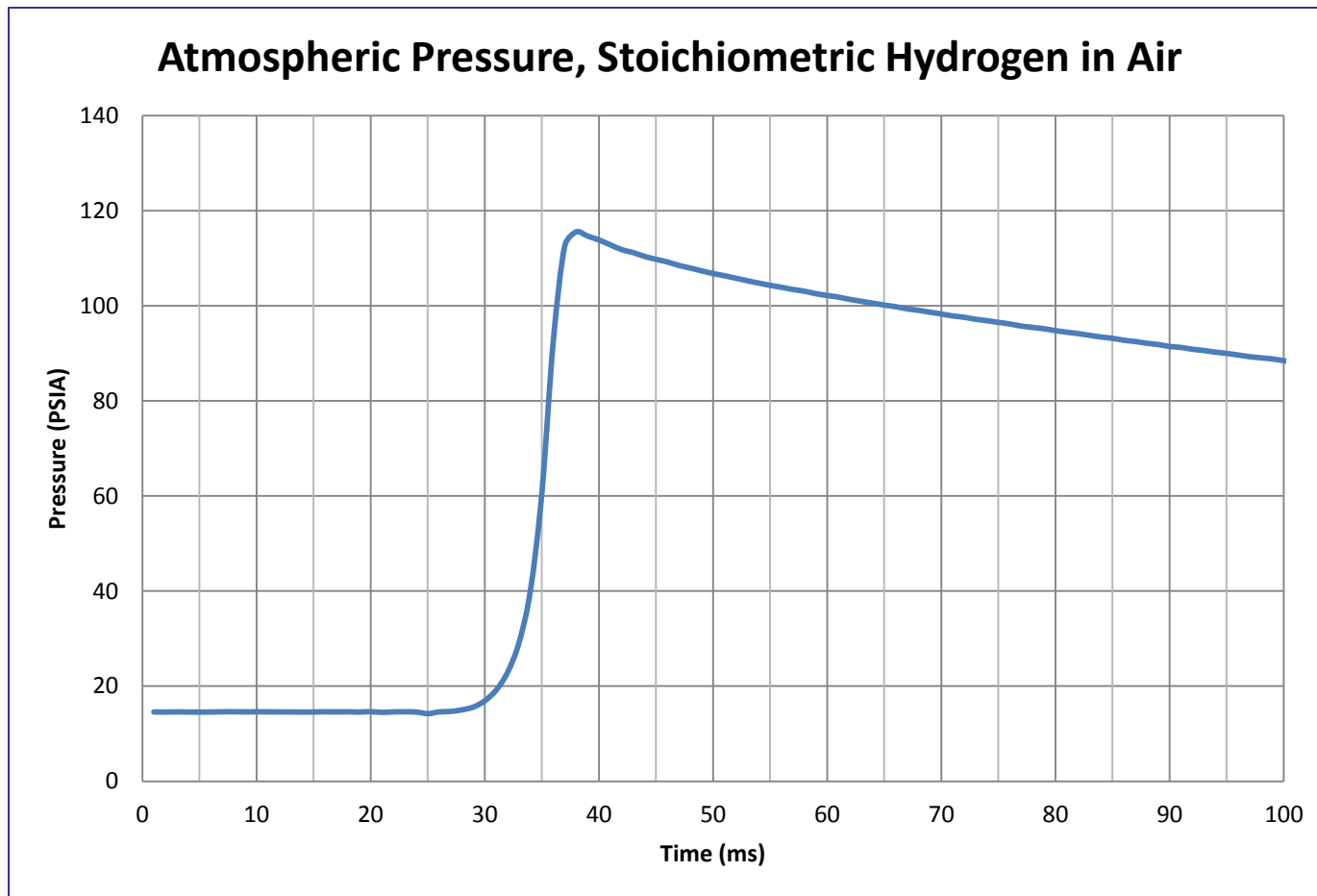
- Flammability limits are wider with larger spark gap
- Final Configuration: 0.65" gap, 0.5s duration, 13.6J average energy

Example of Single Test Pressure Data



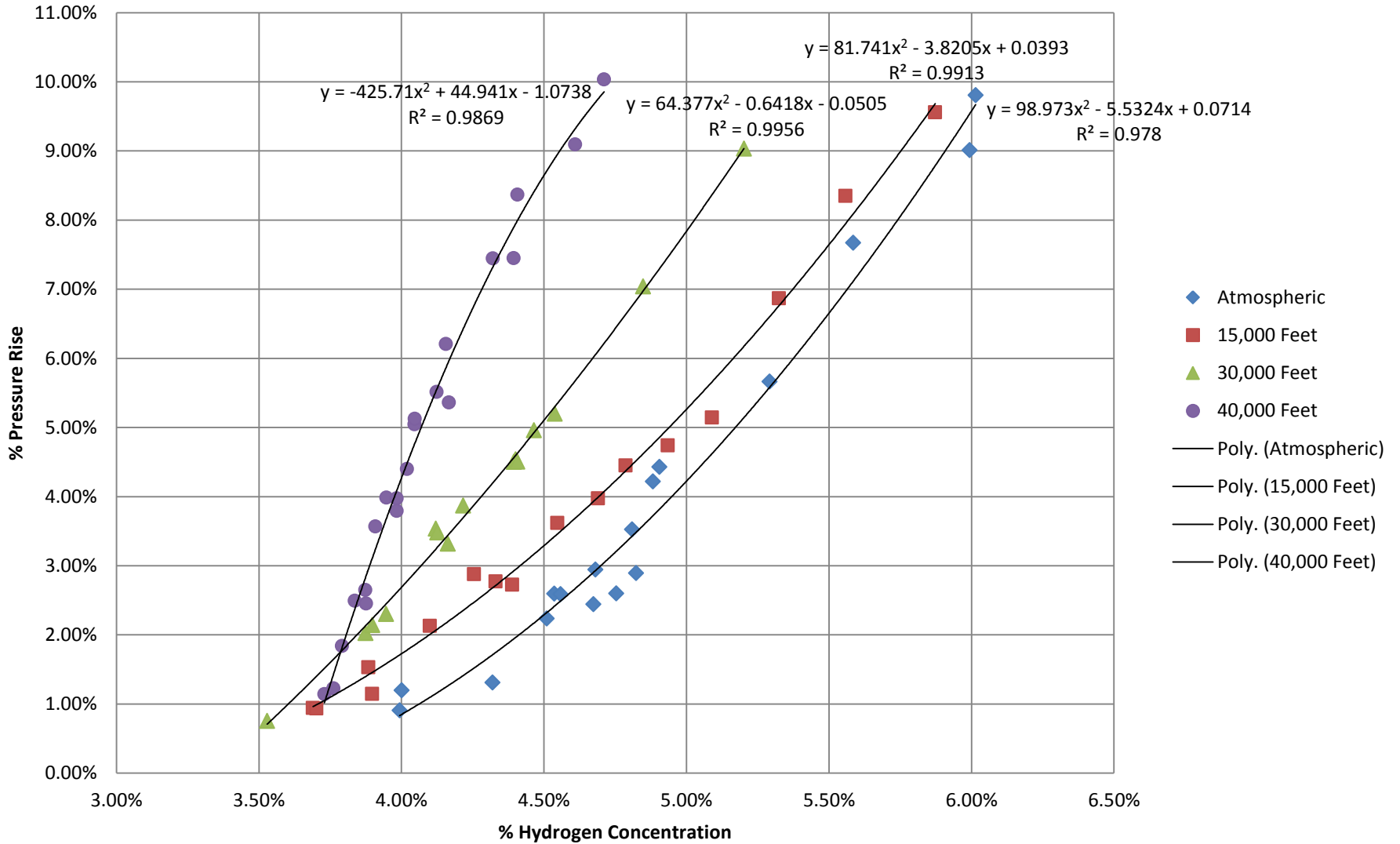
- 3.25% Pressure Rise, 1.1s Rise Time

Example of Single Test Pressure Data

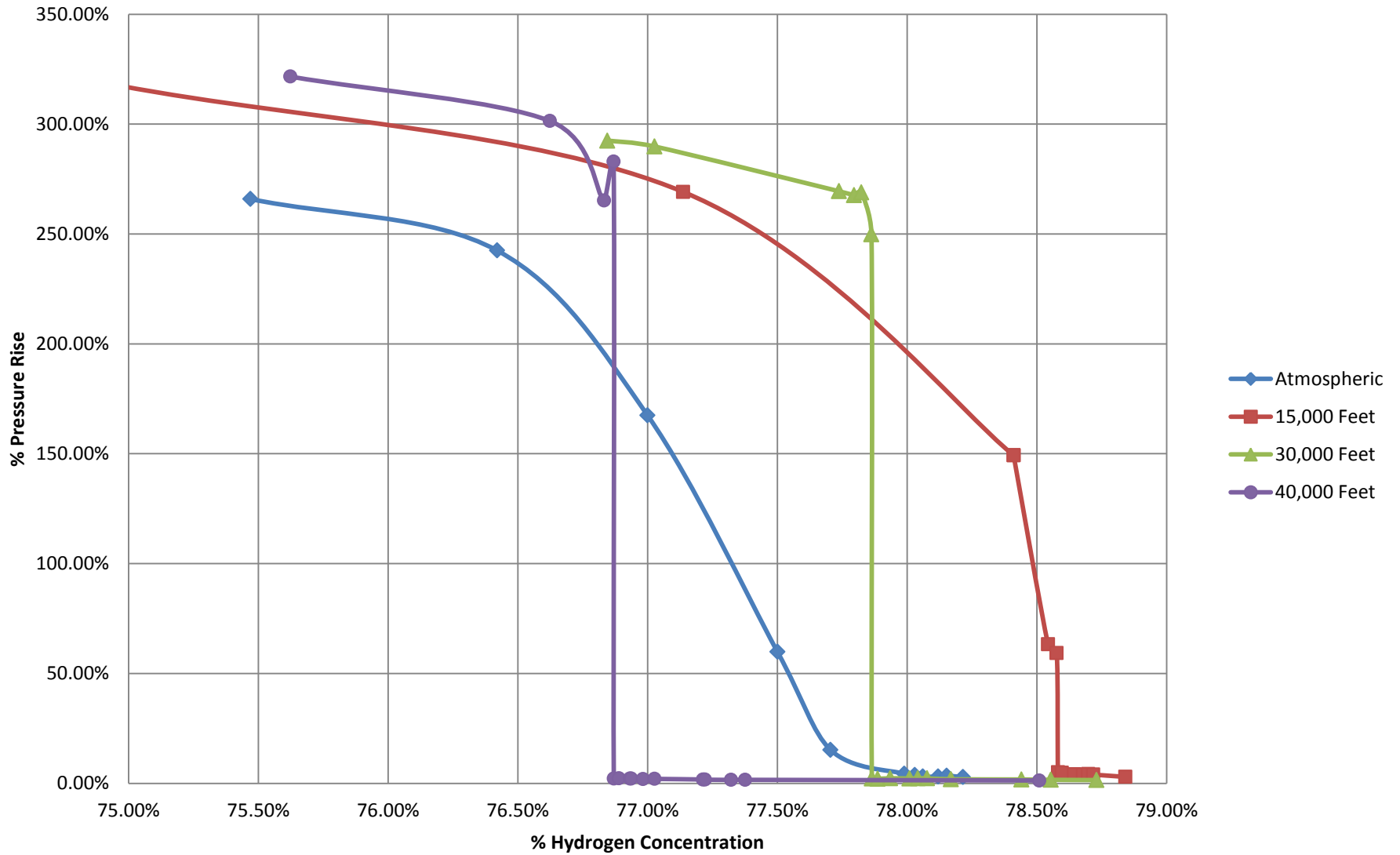


- 686% Pressure Rise, 12ms Rise Time

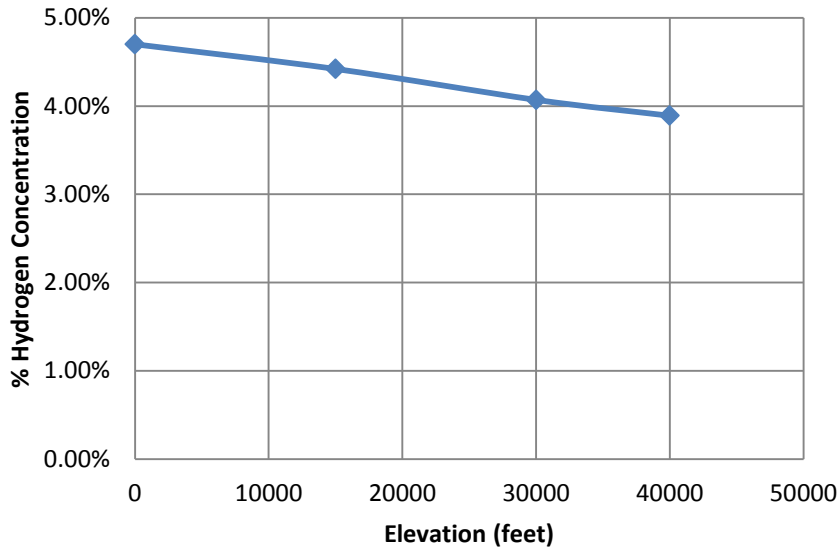
H₂ Lower Flammability Limit vs. Pressure



H₂ Upper Flammability Limit vs. Pressure



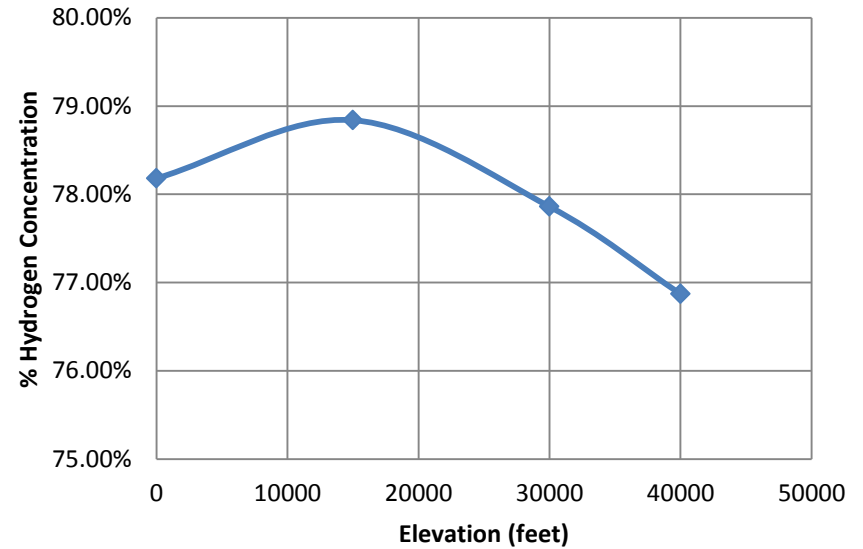
Hydrogen Lower Flammability Limit in Air



Elevation Lean Limit

0	4.70%
15,000	4.42%
30,000	4.07%
40,000	3.89%

Hydrogen Upper Flammability Limit in Air

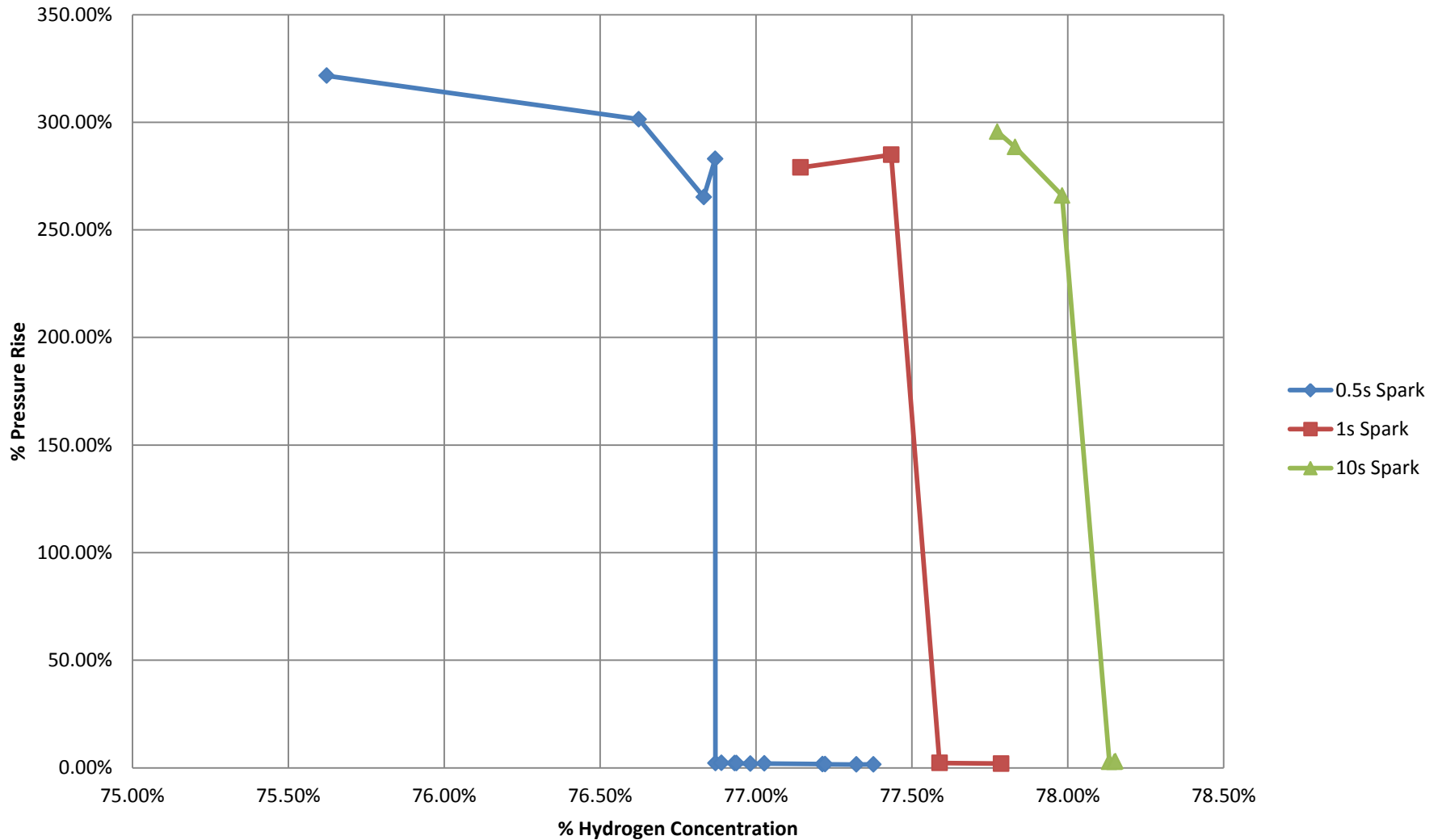


Elevation Upper Limit

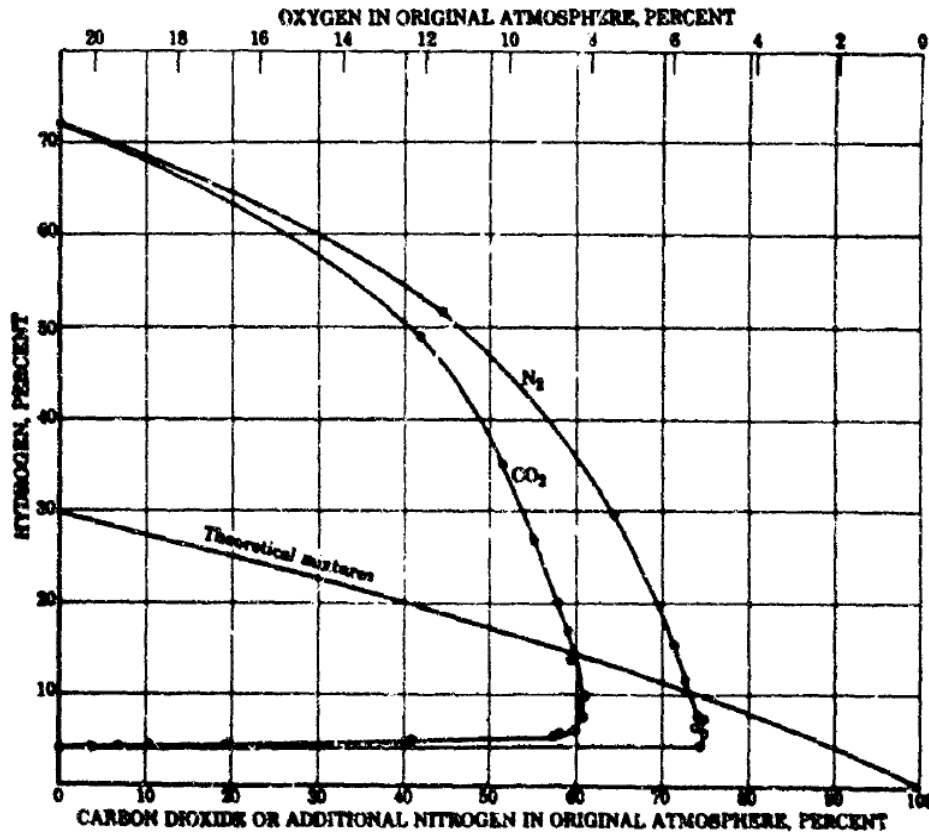
0	78.18%
15000	78.84%
30000	77.86%
40000	76.87%

Not Enough Spark Energy at Low Pressure Upper Flammability Limits

40,000 feet (2.71 PSIA) H₂ Rich Flammability Limit



Inerting with Nitrogen in Literature

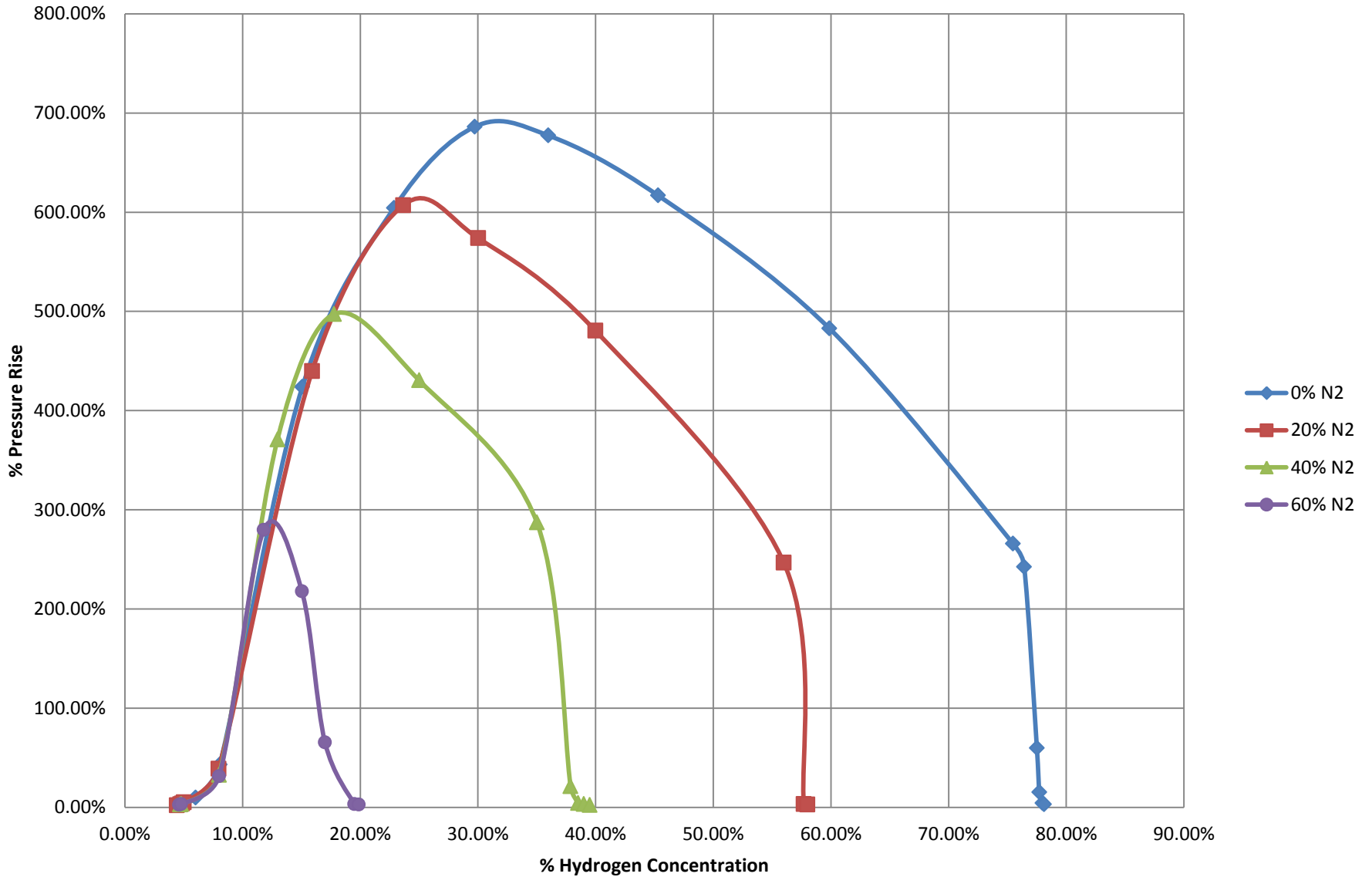


From *Limits of Flammability of Gases and Vapors*,
H. F. Coward and G. W. Jones, Bureau of Mines,
1952.

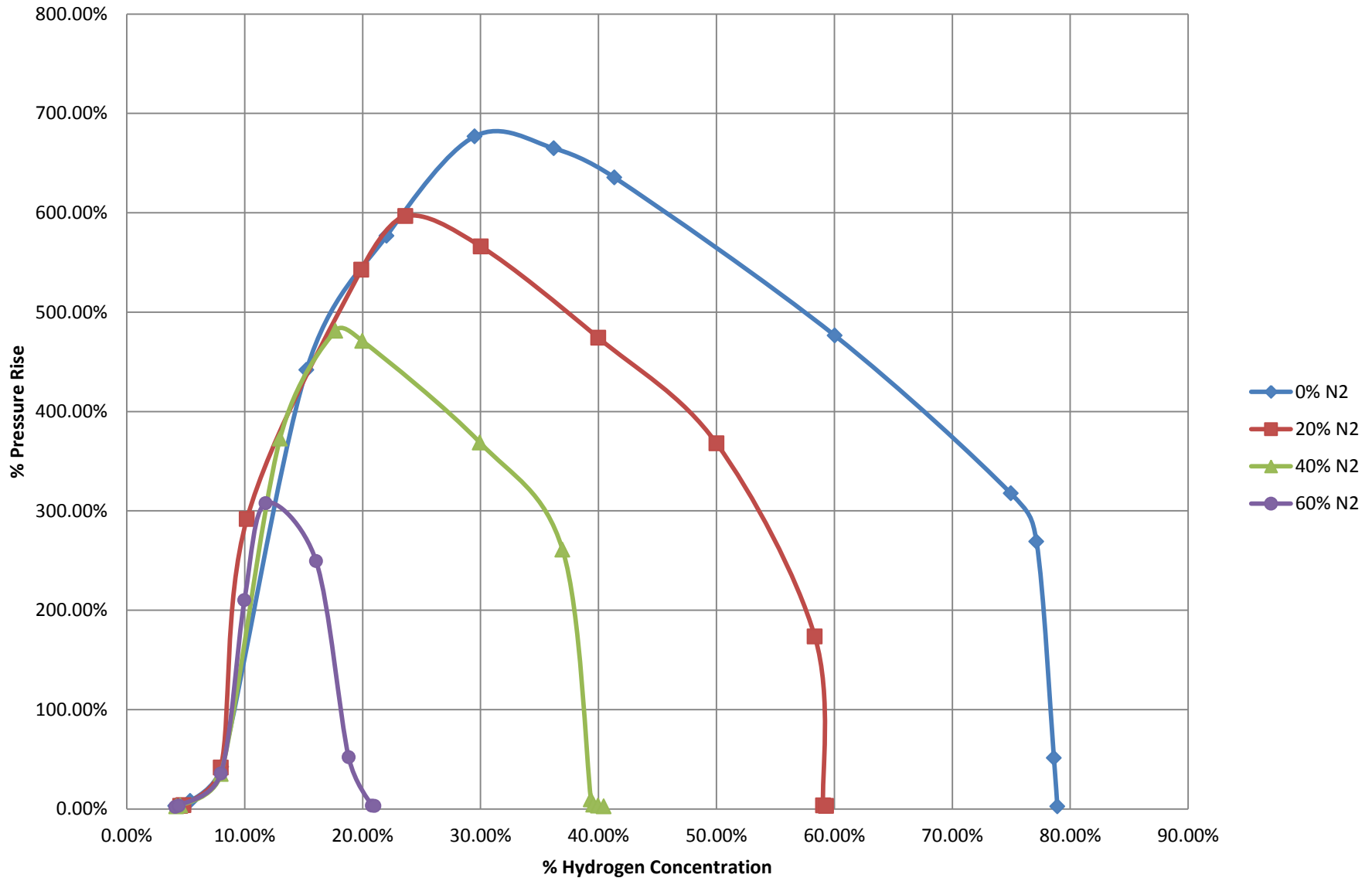
FIGURE 7.—Limits of Flammability of Hydrogen in Air and Carbon Dioxide or Nitrogen.

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

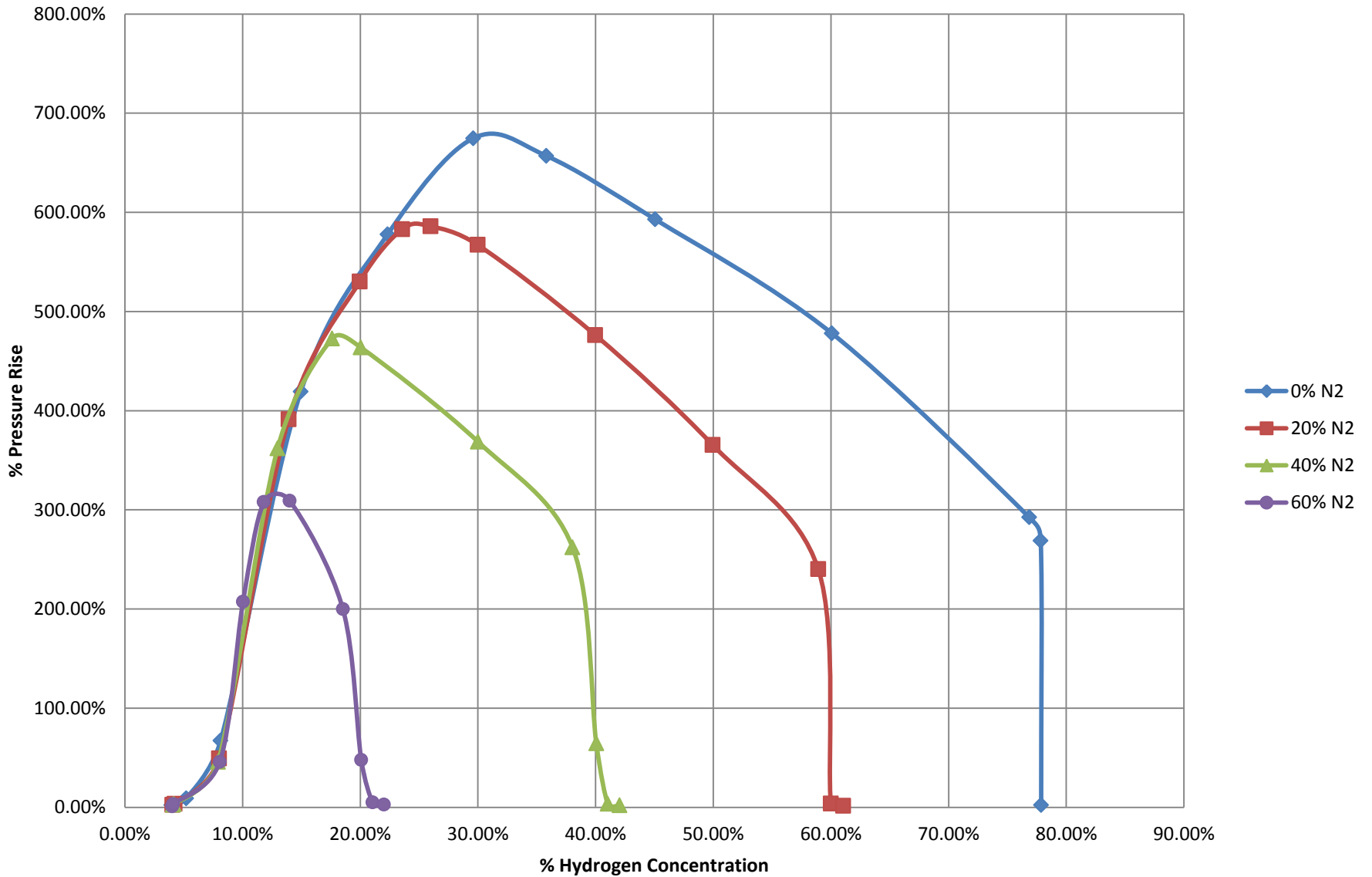
Atmospheric Pressure(14.7PSI) Hydrogen in Oxygen Depleted Air



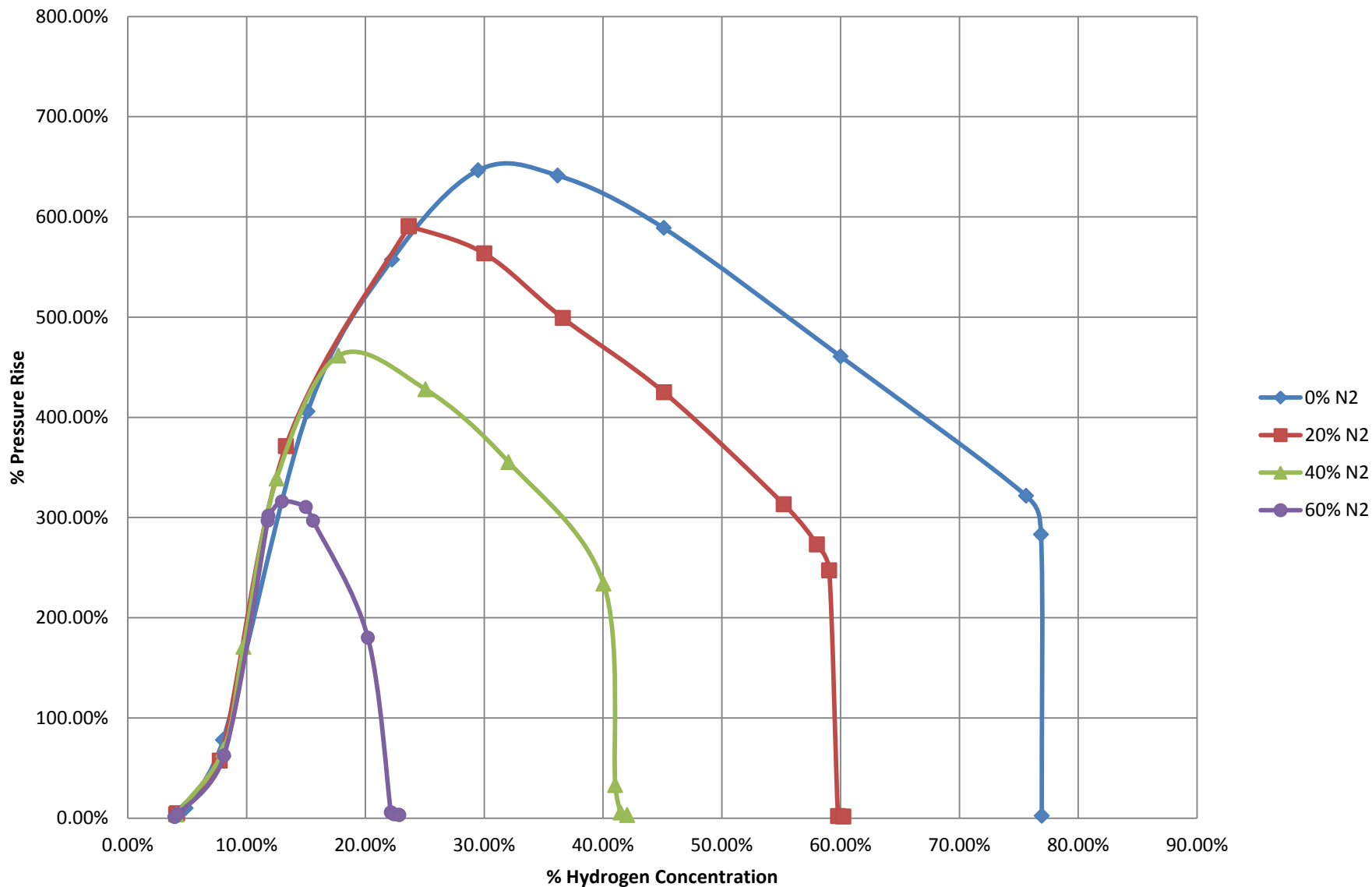
15,000 feet (8.29PSI) Hydrogen in Oxygen Depleted Air



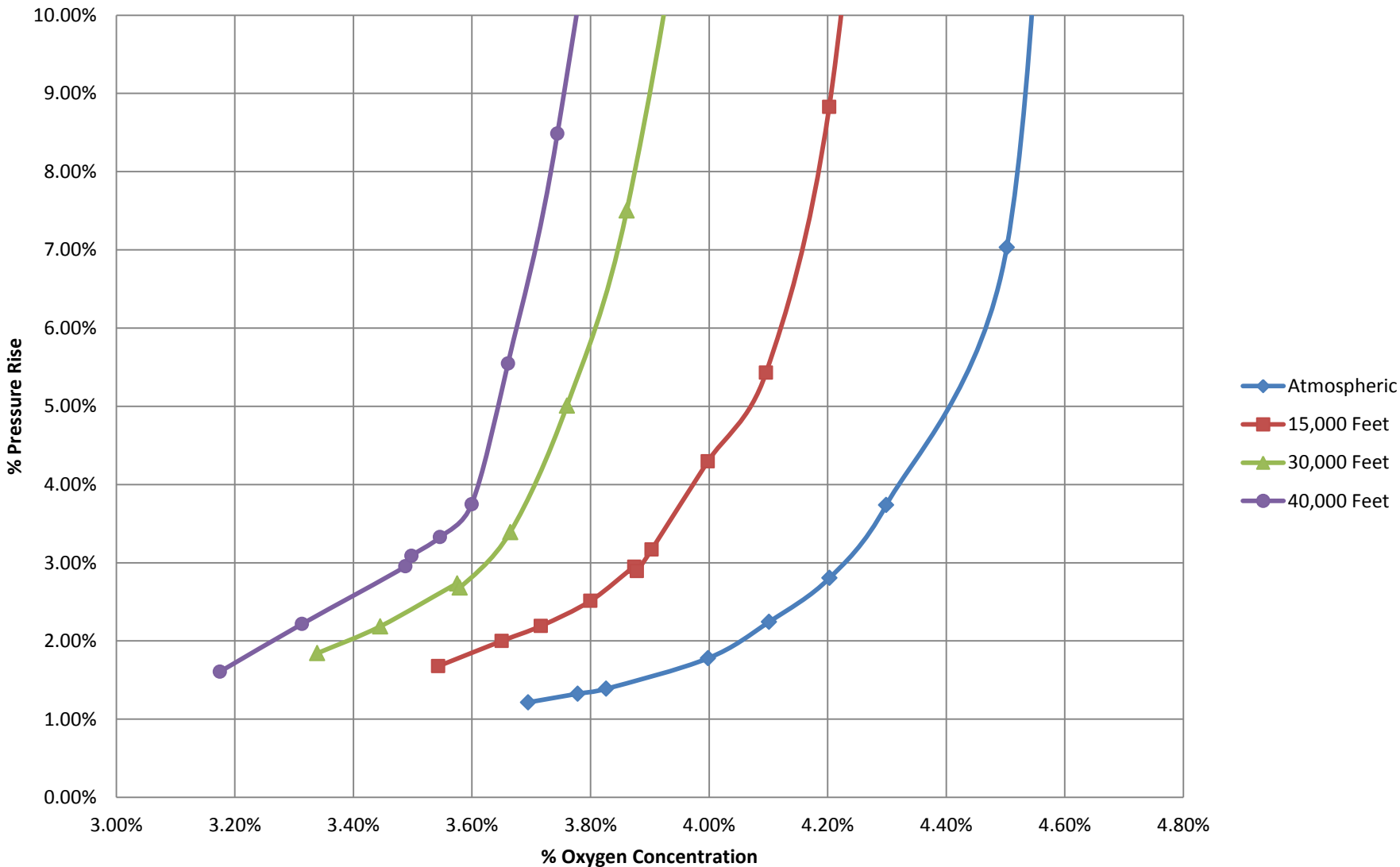
30,000 feet (4.36PSI) Hydrogen in Oxygen Depleted Air



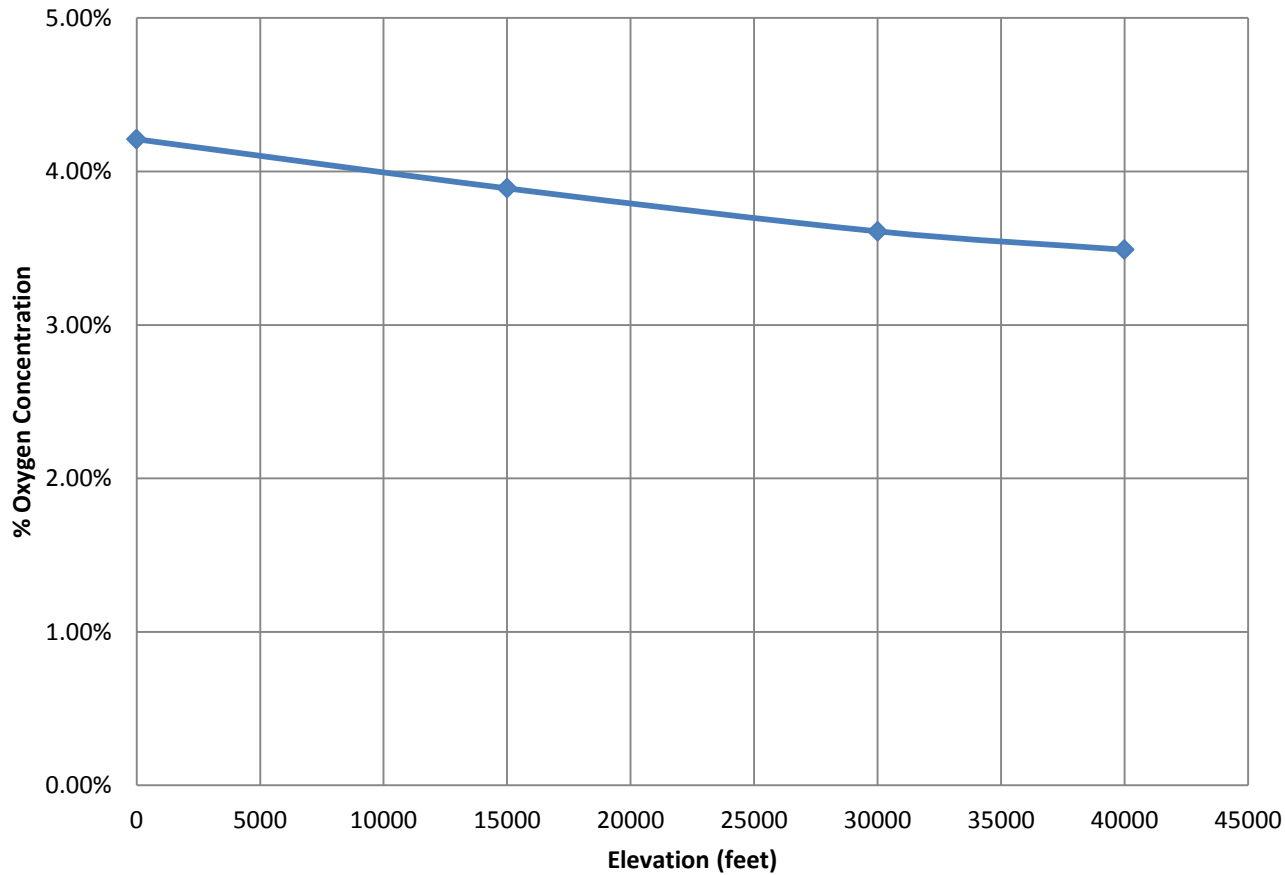
40,000 feet (2.71PSI) Hydrogen in Oxygen Depleted Air



Limiting Oxygen Concentration vs. Pressure

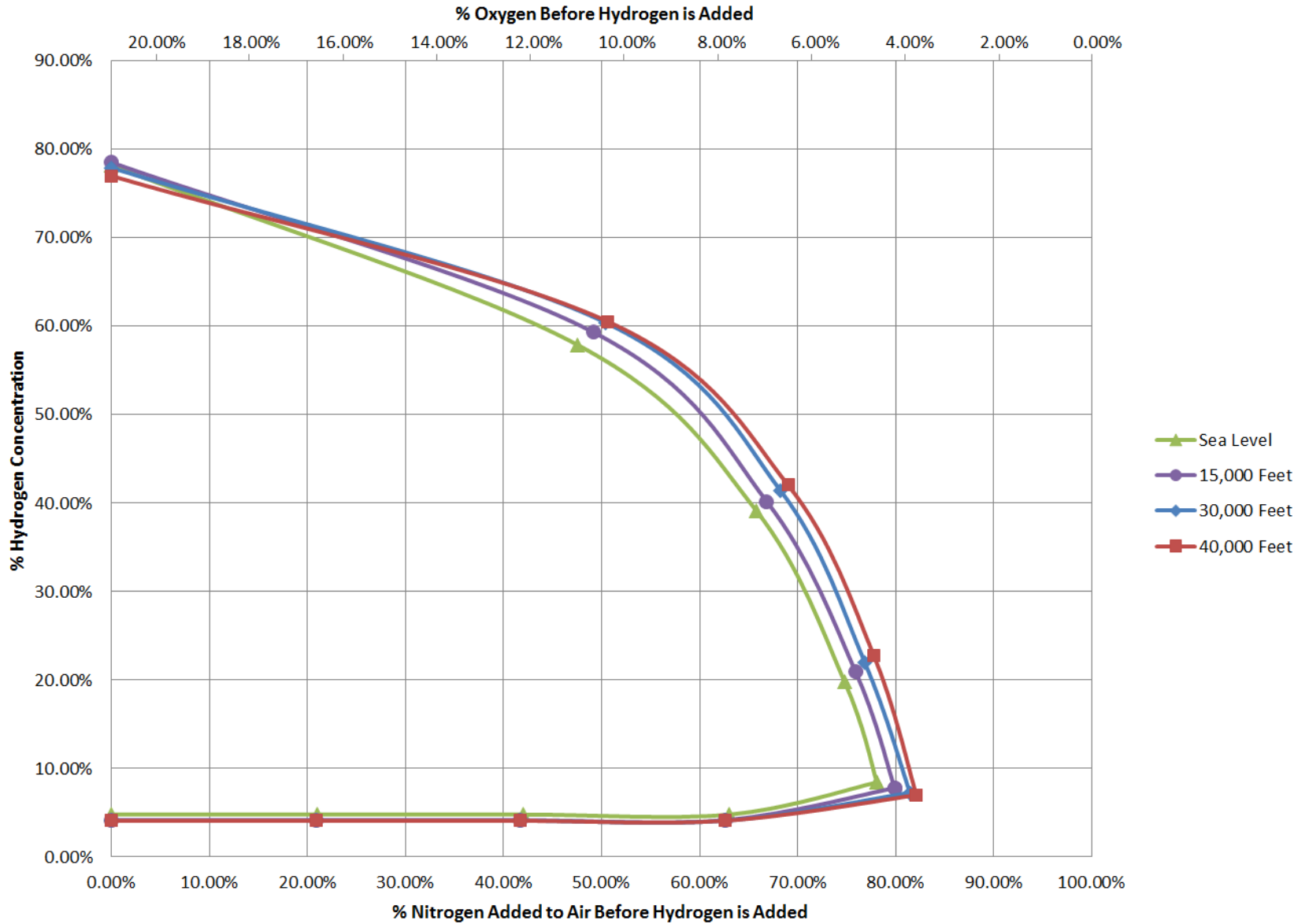


Limiting Oxygen Concentration



Elevation	Limiting O ₂ %
0	4.21%
15000	3.89%
30000	3.61%
40000	3.49%

Hydrogen in Oxygen Depleted Air



Conclusion and Future Work

- **H₂ flammability limits widen at high altitude**
- **H₂ requires less O₂ to ignite at high altitudes, so more N₂ is required to inert it**

- **Higher spark energy needed near upper flammability limits at high altitude**