EVALUATION OF CO$_2$, N$_2$ AND HE AS FIRE SUPPRESSION AGENTS IN MICROGRAVITY

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The U.S. modules of the International Space Station use gaseous CO$_2$ as the fire extinguishing agent. This was selected as a result of extensive experience with CO$_2$ as a fire suppressant in terrestrial applications, trade studies on various suppressants, and experiments. The selection of fire suppressants and suppression strategies for NASA's Lunar and Martian exploration missions will be based on the same studies and normal-gravity data unless reduced gravity fire suppression data is obtained. In this study, the suppressant agent concentrations required to extinguish a flame in low velocity convective flows within the 20-sec of low gravity on the KC-135 aircraft were investigated. Suppressant gas mixtures of CO$_2$, N$_2$, and He with the balance being oxygen/nitrogen mixtures with either 21% or 25% O$_2$ were used to suppress flames on a 19-mm diameter PMMA cylinder in reduced gravity. For each of the suppressant mixtures, limiting concentrations were established that would extinguish the flame at any velocity. Similarly, concentrations were established that would not extinguish the flame. The limiting concentrations were generally consistent with previous studies but did suggest that geometry had an effect on the limiting conditions. Between the extinction and non-extinction limits, the suppression characteristics depended on the extinguishing agent, flow velocity, and O$_2$ concentration. The limiting velocity data from the CO$_2$, He, and N$_2$ suppressants were well correlated using an effective mixture enthalpy per mole of O$_2$, indicating that all act via O$_2$ displacement and cooling mechanisms. In reduced gravity, the agent concentration required to suppress the flames increased as the velocity increased, up to approximately 10 cm/s (the maximum velocity evaluated in this experiment). The effective enthalpy required to extinguish flames at velocities of 10 cm/s is approximately the same as the concentrations in normal gravity. A computational study is underway to further evaluate these findings.

Assessment of CO_2, N_2, and He as Suppressants in Microgravity Environments

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Fire Suppression on ISS

Carbon Dioxide is the current suppressant of choice on the ISS. The requirements were developed based on NFPA 12 Regulations that specify that a 50% concentration by volume are required to extinguish smoldering fires (with a 20 minute hold). A concentration of 30% by volume was required to extinguish flaming fires. Carbon dioxide was selected through trade studies that evaluated suppressants based on:

- **Effectiveness on potential spacecraft fires**
- **Reliability**
- **Maintainability**
- **System Weight**
- **Required post-fire clean-up**
- **Compatibility with other spacecraft systems**
- **Toxicity of suppressant and/or post-fire suppression products**

These studies generally conclude that CO_2 and N_2 are close in acceptability with the first choice depending on the weighting of the above criteria. These studies also recommend use of a water-based suppressant should be used for smoldering fires.

Normal-gravity tests were conducted by Sircar *et al.* (1992) that evaluated CO_2, He, N_2, and Halon in a NASA STD 6001 Test 1 configuration (Upward Flame Propagation) with quiescent delivery of the suppressant mixture. Halon was the most effective followed by CO_2. N_2 and He were equally less effective.

ISS Portable Fire Extinguisher
(6 lbs of CO_2 at 850 psi; discharges in 45 sec)

Motivation and Objectives

- Fire response procedure on ISS dictates that ventilation flow is ceased and power removed after annunciation of a fire alarm
- Discharge of a fire extinguisher will induce flow with varying CO_2 concentration
- Effectiveness of these suppressants has never been evaluated in low-velocity convective flows (up to 10-15 cm/s) in microgravity
- Design of next generation, exploration spacecraft will ask the same questions with little new data
- ➢ Determine the effectiveness of the flow of CO_2, He, and N_2 to suppress fires in microgravity
- ➢ Conduct tests on the KC-135 on PMMA cylinders for a variety of suppressants and suppressant mixtures

Spacecraft Fire Safety Facility

- **Combustion Chamber**
  - (25.4 cm diam, 51 cm high)
- **Flows up to 17 cm/s**
  - Three mass flow controllers
    - Two 500 slpm
    - 2000 slpm
- **Pressure up to 3 atm**

Test Matrix and Samples

- Chamber Pressure = 1 atm
- Standard Air - 21% O_2, 79% N_2
- Rich Air - 25% O_2, 75% N_2
- Velocity: 1 – 10 cm/s

- 19.1 mm diam x 25.4 mm long PMMA cylinders
- Cartridge heater through center
- Surface and heater t/c

- Hot wire igniter
- Flow from bottom to top

Oxidizer	Suppressant	Concentrations (% vol)
Standard Air	CO_2	12.5%, 25%
	He	12.5%, 25%
	N_2	25%
Rich Air	CO_2	12.5%, 25%
	He	12.5%, 25%
	N_2	25%

Sample

Igniter
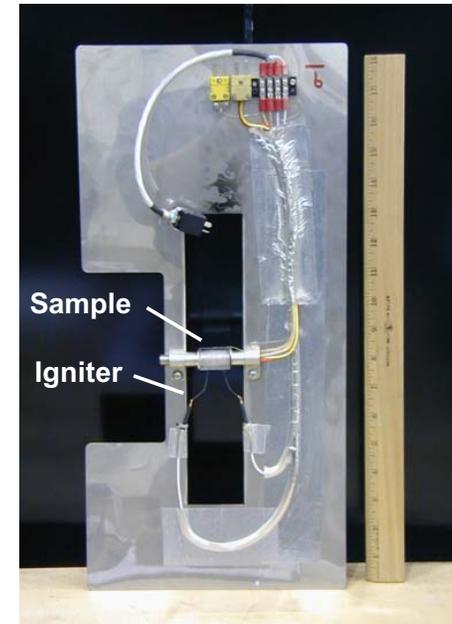
Sample card with sample and cartridge heater

1.1 cm/s

3.2 cm/s

4.2 cm/s

5.2 cm/s

7.6 cm/s
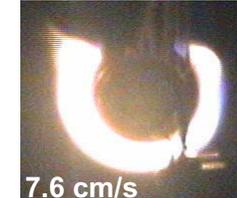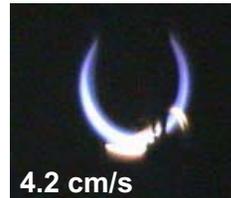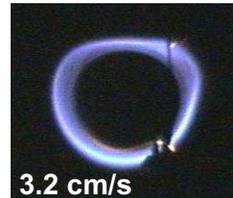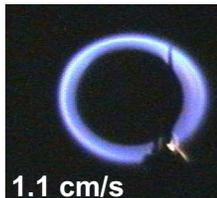
Typical low-g flames for 25% O_2, 75% N_2

Microgravity Results
CO_2, He, N_2 Suppressants

- **Suppressant mole fraction / mole fraction of O_2 as a function of velocity ...**
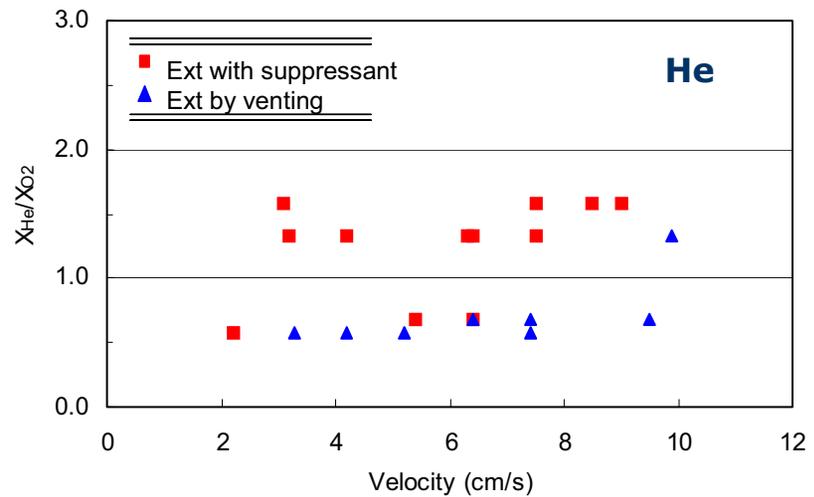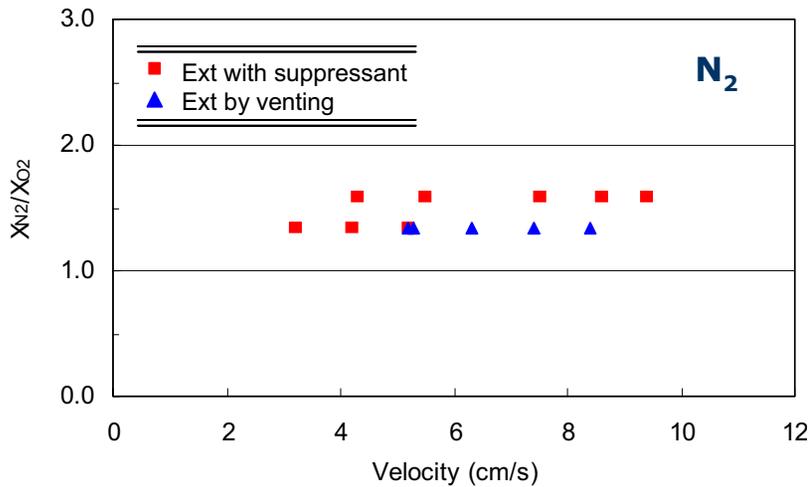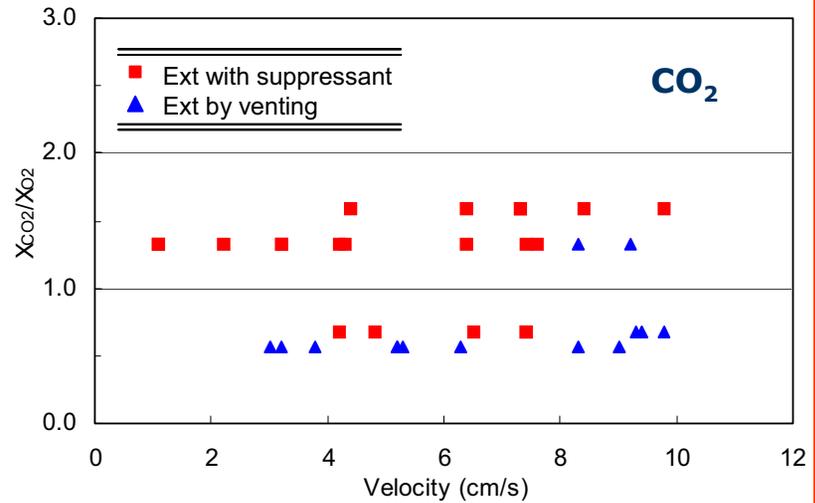 - Extinguishment limits in slow flow regime (i.e., less than 10 cm/s) show dependence on velocity
  - Previous studies ...

    CO_2 : X_{CO2} / X_{O2} = 0.62 (Prasad *et al.*)

    X_{CO2} / X_{O2} = 1.12 (Takahashi *et al.*.)

    He : X_{He} / X_{O2} = 2.1 (Takahashi *et al.*)

    N_2: X_{N2}/X_{O2}=2.92 (Takahashi *et al.*)
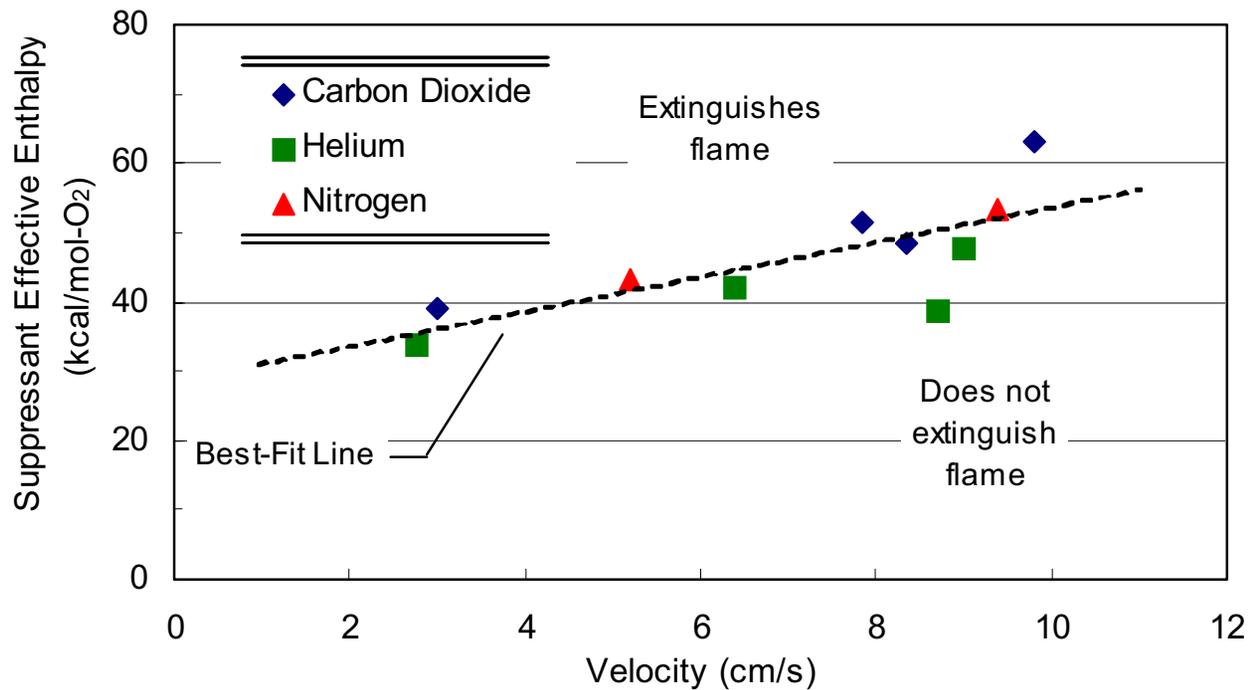
Effective Enthalpy/Mol O$_2$

- **Huggett (1969, 1973) proposed a "threshold" heat capacity above which organic fuels cease to burn**
  - Showed that at a "mixture" specific heat greater than 40 – 50 cal/C-mol O$_2$ a flame <u>could not</u> be sustained (at a pressure of 1.0 atm)
  - Determined from strained laminar diffusion flames

- **Sheinson *et al*. (1989) applied this concept to evaluate the physical and chemical performance of various suppressant mixtures**
  - Defined an effective mixture enthalpy as energy required to heat mixture from 298 K to 1600K

$$\Delta H' = \sum_i \frac{X_i}{X_{O2}} \int_{298}^{1600} Cp_i \, dT$$

- **Calculated the effective enthalpy/mol O$_2$ for each suppressant mixture**
- **Established a limiting velocity at which there was a transition in suppression characteristics**
  - Averaged bounding velocities
  - Plotted highest velocity tested if no transition was observed

Correlation with Effective Enthalpy

- Helium lies slightly below CO_2 and N_2 presumably because of higher thermal conductivity
- Microgravity flame on PMMA requires less suppressant to extinguish at lower velocities
- Normal gravity suppression is at 63.2 kcal/mol O_2

Conclusions

- **Higher suppressant concentrations are required to extinguish flames in microgravity as velocity increases**
  - Up to 10 cm/s investigated in this experiment
  - Effective enthalpy/mol-O_2 correlates limiting velocity fairly well
  - Effective enthalpy at 10 cm/s is nearly normal-gravity value
- **For these conditions, CO_2, N_2, and He all act as passive suppressants**
  - O_2 replacement and cooling
- **Procedures on ISS are reasonable for flaming fires**
  - Specifications for CO_2 concentrations are high enough for smoldering fires but no provision for hold time
  - Use of water-based foam in U.S. modules is not "recommended"

Future Work

- **Continue modeling of the CO_2, He, and N_2 suppression results**
  - Can the suppression and limiting velocity boundaries be duplicated?
- **Complete analysis of partial gravity suppression data**
  - Data obtained for CO_2 at 0.1-g_o, 0.17-g_o(Lunar), 0.38-g_o (Martian), and 0.5-g_o