EVALUATION OF CO₂, N₂ AND HE AS FIRE SUPPRESSION AGENTS IN MICROGRAVITY

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The U.S. modules of the International Space Station use gaseous CO₂ as the fire extinguishing agent. This was selected as a result of extensive experience with CO₂ 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 CO₂, N₂, and He with the balance being oxygen/nitrogen mixtures with either 21% or 25% O₂ 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 O₂ concentration. The limiting velocity data from the CO₂, He, and N₂ suppressants were well correlated using an effective mixture enthalpy per mole of O₂, indicating that all act via O₂ 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 CO₂, N₂, 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.
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 CO₂ 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 CO₂, He, and N₂ 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% O₂, 79% N₂
- Rich Air - 25% O₂, 75% N₂
- Velocity: 1 – 10 cm/s
- Hot wire igniter
- Flow from bottom to top

<table>
<thead>
<tr>
<th>Oxidizer</th>
<th>Suppressant</th>
<th>Concentrations (% vol)</th>
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<tbody>
<tr>
<td>Standard Air</td>
<td>CO₂</td>
<td>12.5%, 25%</td>
</tr>
<tr>
<td></td>
<td>He</td>
<td>12.5%, 25%</td>
</tr>
<tr>
<td></td>
<td>N₂</td>
<td>25%</td>
</tr>
<tr>
<td>Rich Air</td>
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<td></td>
<td>N₂</td>
<td>25%</td>
</tr>
</tbody>
</table>

Sample card with sample and cartridge heater

Typical low-g flames for 25% O₂, 75% N₂
Microgravity Results

\( \text{CO}_2, \ \text{He}, \ \text{N}_2 \) Suppressants

- Suppressant mole fraction / mole fraction of \( \text{O}_2 \) as a function of velocity ...
  - Extinguishment limits in slow flow regime (i.e., less than 10 cm/s) show dependence on velocity
  - Previous studies ...
    - \( \text{CO}_2 \) : \( X_{\text{CO}_2} / X_{\text{O}_2} = 0.62 \) (Prasad et al.)
    - \( X_{\text{CO}_2} / X_{\text{O}_2} = 1.12 \) (Takahashi et al.)
    - \( \text{He} \) : \( X_{\text{He}} / X_{\text{O}_2} = 2.1 \) (Takahashi et al.)
    - \( \text{N}_2 \) : \( X_{\text{N}_2} / X_{\text{O}_2} = 2.92 \) (Takahashi et al.)
Effective Enthalpy/Mol O\textsubscript{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\textsubscript{2} a flame could not 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\textsubscript{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 CO₂ and N₂ 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 O₂
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$_o$