An Overview of Smoke Detection and Spacecraft Fire Safety in Low Gravity

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Why are spacecraft fires so dangerous?

• Typical fire safety strategies for crew (e.g., escape options) are more challenging

• Lack of gravity challenges early-stage fire detection

• Lack of gravity can change propagation of the fire itself

• Post-fire cleanup of toxic combustion products challenged by low gravity and limited short-term resources → long term health effects for crew


Image taken by Dr. Jerry Linenger following Mir fire; spaceflight.nasa.gov/history/shuttle-mir/multimedia/linenger-photos/linenger-p-003.htm
How are fires different in microgravity?

Without gravity, flames are unaffected by buoyancy.

- Material flammability limits are lower in microgravity than terrestrial gravity
- Changes in flame \(\rightarrow\) changes in combustion products
  - **Particle transport and evolution:** Lack of settling and buoyancy \(\rightarrow\) longer particle residence times within and outside the flame \(\rightarrow\) larger particles
Microgravity Smoke Detection Challenges

- Challenges with detector **placement** (no buoyancy $\rightarrow$ smoke does not rise)
- Plume dilution and slower propagation through volume $\rightarrow$ **opportunity for fire to grow** prior to detection
- **False alarms** from background particles (no gravitational settling)

*Urban et al., 46th Int. Conf. Environ. Sys., Vienna, Austria, ICES-2016-318, July 2016.*
Characterizing Particles from Microgravity Fires

• Need to detect smoke before a flame grows:
  • Target particles from smoldering rather than flaming combustion
  • Identify relevant particle sizes/morphologies by measuring smoke particles from spacecraft-relevant “fire-resistant” materials
  • Evaluate detector performance for these particles

• Smoke Aerosol Measurement Experiment (SAME): measured particle sizes and morphologies in microgravity

SAME Publications:
• Meyer et al., Fire Safety Journal, 98. 74-81, 2018.
SAME key findings:

- All tested fuels produced substantial PM1
- Particle dynamics predominated by factors other than gravity (e.g., changes in air flow alters coagulation rates)
- Detector response dependent on particle size and mechanism of detection:
  - ISS forward light scattering detector had diminished response to smallest particles (Kapton and Teflon, <300 nm)
  - Ionization detector had slightly better response to smallest particles (particularly Teflon)

Material images: Marit Meyer
Characterizing Particles from Microgravity Fires

Ongoing experiments: Spacecraft Fire Safety experiments (Saffire)

• Opportunity to study **large-scale fires** in microgravity with **lower risk to crew**

• Saffire I-III (2016-2017):
  • Measured flame spread rate, fuel mass consumption, heat release

• Saffire IV-VI (2020-2021; in progress):
  • In addition to flame properties, measure **combustion products** from variety of fuels
  • Test **post-fire cleanup** technology

*Image credits: NASA*
Detection Challenges: Smoke Detector Performance

- ISS smoke detector: **forward light scattering**;
  Space shuttle (ret. 2011) smoke detector: **radioisotope ionization**

- Detector standards typically **based on Earth standards** (e.g., Underwriters’ Laboratory #217 and #268)

- Problem: compared to terrestrial applications, **early detection is especially critical** and minimum concentration detection thresholds must be small

12CO.9 (Wed 10/7, 6:00-7:30PM EDT): Wang et al., “Laboratory-Generated Aerosols as Transfer Standards to Characterize Smoke Detector Performance”

Detection Challenges: Influence of Vehicle Characteristics

If a fire breaks out, **what determines the time to alarm?**

- **Brooker et al. (2007):** modeled ventilation flow and detector response in ISS Destiny
  - Proximity of smoke source to detector was unreliable predictor of alarm time
  - **Alarm times dictated by air flow patterns**
- **Dietrich et al. (2012, 2013):** outcomes (e.g., long and short-term survivability) depend on parameters specific to vehicle
  - No “one size fits all” solution for successful detection and suppression
- **Urban et al. (2016):** compared smoke/heat release rates with mixing and filtration rates
  - How much material must be smoldered to trigger an alarm?
  - HEPA filtration in ISS greatly increases time to alarm123- **Toxic gases could have opportunity to accumulate in mixing volume before alarm even sounds**

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**ISS ECLSS: life support system, including atmospheric regulation and fire detection/suppression**

Urban et al., 46th Int. Conf. Environ. Sys., Vienna, Austria, ICES-2016-318, July 2016.
Detection Challenges: Reducing False Alarms

- Dietrich et al. (2017): certain activities can generate particle concentrations high enough to induce false alarms

- Suggested strategies:
  - Urban et al. (2016): Measure combustion gas (e.g., CO) in parallel with particles
  - Schultze et al. (2020): Improve detector design to optically distinguish smoke particles from dust based on particle morphology
  - Future deep-space missions: light scattering detector with threshold based on rate of rise


Urban et al., 46th Int. Conf. Environ. Sys., Vienna, Austria, ICES-2016-318, July 2016.

Future Challenges: Lunar Missions

In future lunar missions (e.g., Artemis), will need to **distinguish smoke particles from lunar dust**.

- Park et al. (2008): lunar dust samples from Apollo missions have lognormal distribution, with **modes 100-200 nm**
  - Distinguishing smoke and dust particles for smoke detection based on size could be challenging
- Lunar dust ($d_p < 20 \mu m$) is harmful to crew health
  - Sharp, irregularly-shaped shards
  - During Apollo missions, astronauts experienced eye, nose, throat irritation
  - **Health effects will dictate air flow and filtration strategies**

Future Challenges: Lunar Missions

- Lunar gravity ~ 1/6 g
  - Some buoyant flow and settling expected, but **smaller particles will stay in air for longer**
  - Sacksteder and T’ien (1994): “flammability zone” different in partial-g compared to either 1g or 0g, but limited data exist

- Novel mission parameters → new risks
  - Longer mission durations → need to store more oxygen and/or ignitable/reactive materials (e.g., batteries)
  - **Increased extravehicular activities** → oxygen handling, dust transport, use of oxygen to mitigate decompression sickness, etc.

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Image credit: NASA, Artemis Lunar Exploration Program Overview
nasa.gov/specials/artemis/
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Extra Slides
Meyer et al. (2015) describes “moment method” for determining particle size distributions:

- “Zeroth Moment” = particle number concentration
- “First Moment” = number average particle diameter
- “Third Moment” = particle volume (and mass) concentration
- If you have three moments, and assumptions about particle properties hold (e.g., spherical shape), particle size distributions can be approximated.
- SAME experiments: moment method works well only for spherical particles
<table>
<thead>
<tr>
<th>System</th>
<th>Detector Performance Basis</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>Minimum Sensitivity 1.6 to 13.2 % obscuration/m plus test fires</td>
<td>Light Scattering or Ionization</td>
</tr>
<tr>
<td>FAA Cargo Bay</td>
<td>Emphasis on sampling the cargo area and false alarm avoidance, typical range is up to 13.2 % obscuration/m</td>
<td>Predominantly Light Scattering</td>
</tr>
<tr>
<td>Space Shuttle</td>
<td>2 mg/m³ [8]</td>
<td>Ionization</td>
</tr>
<tr>
<td>ISS</td>
<td>3.3 % obscuration/m [8]</td>
<td>Light Scattering</td>
</tr>
<tr>
<td>Orion</td>
<td>Current concept is rate of rise detection (light scattering)</td>
<td>Light Scattering</td>
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</tbody>
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Table 1: Detector Performance Requirements for Terrestrial and Spacecraft Systems