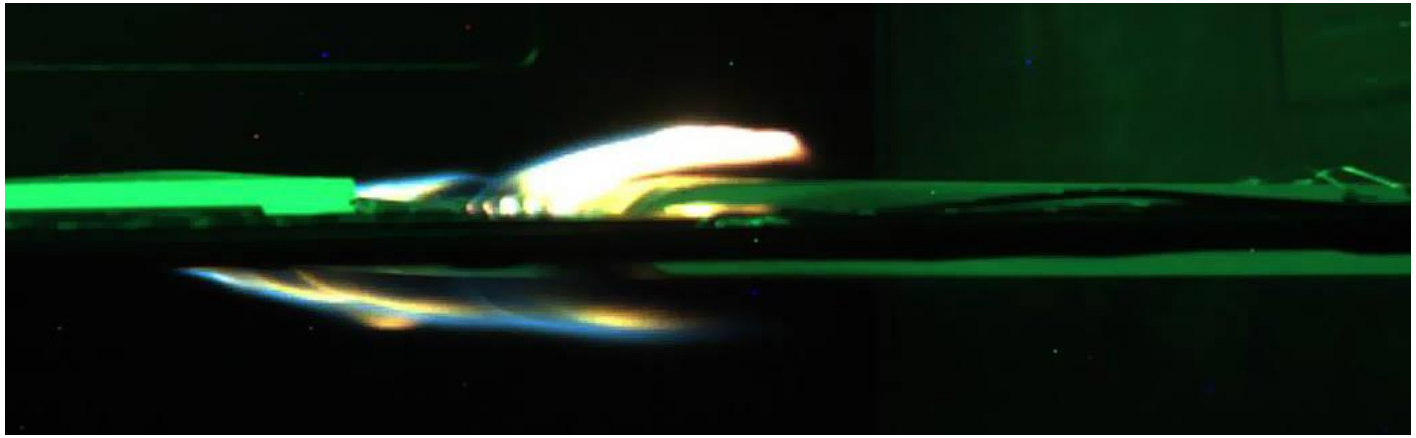
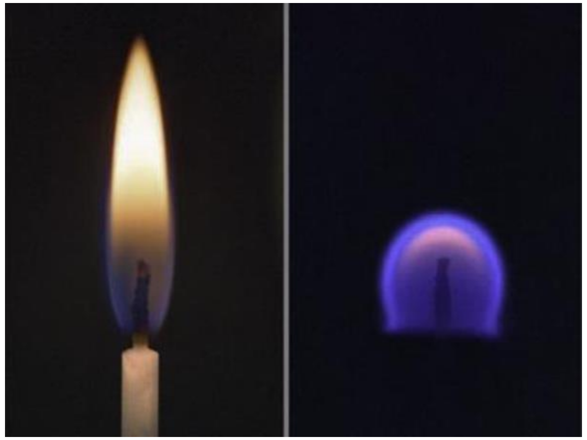
Progress and Challenges in Spacecraft Fire Detection





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June 15, 2022

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Why are spacecraft fires so dangerous?

Mir Space Station Fire:
February 23-24, 1997

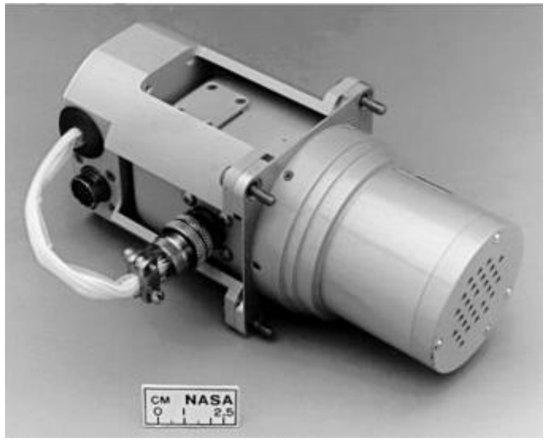
Image taken by Dr. Jerry Linenger following Mir fire; spaceflight.nasa.gov/history/shuttle-mir/multimedia/linenger-photos/linenger-p-003.htm

- Crew **fire safety strategies** are more challenging
- Reduced gravity **challenges early-stage fire detection**
- Reduced gravity can **change characteristics 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**

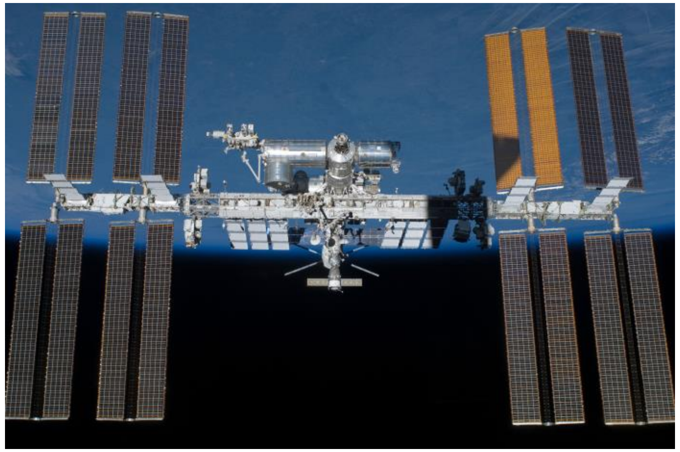
Spacecraft Fire Detection History

- Mercury, Gemini, Apollo: no fire detection systems (short mission durations)
- Skylab: UV fire detector
  - Big issue: false alarms
- Space Shuttle: ionization detector
- ISS: photoelectric detector
  - Light scattering calibrated to an obscuration alarm threshold

Spacecraft fire detection systems developed based on most advanced terrestrial technology of the time



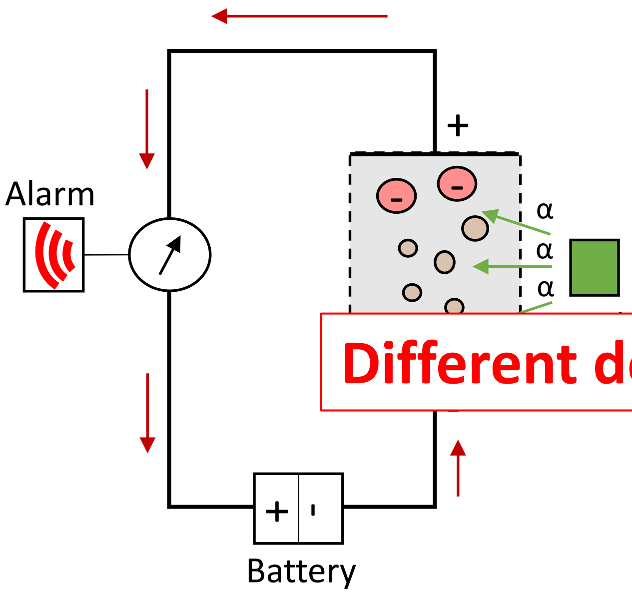
https://www.nasa.gov/mission_pages/shuttle/flyout/shuttleachievements.html

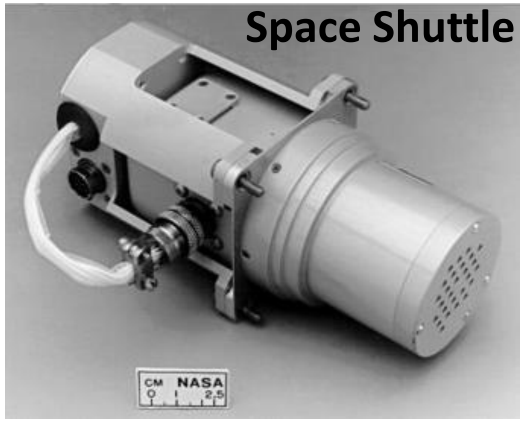


https://www.nasa.gov/mission_pages/station/main/index.html

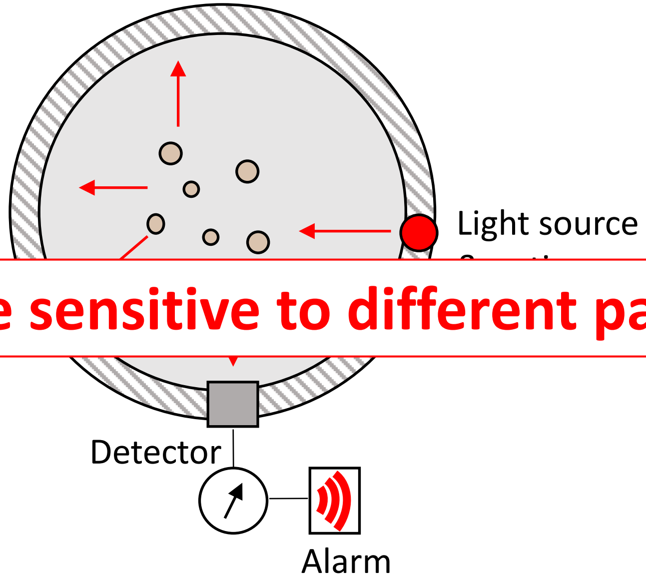
Smoke Detection Methods

Ionization

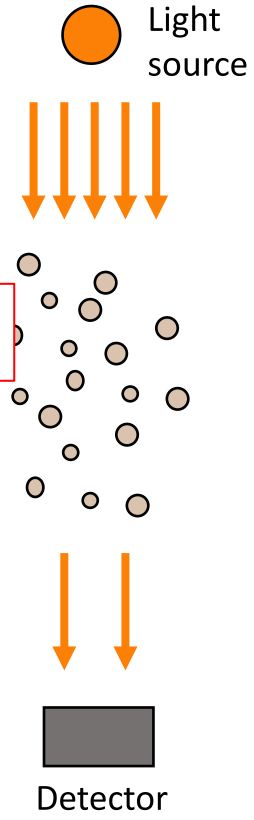




Light Scattering



Obscuration



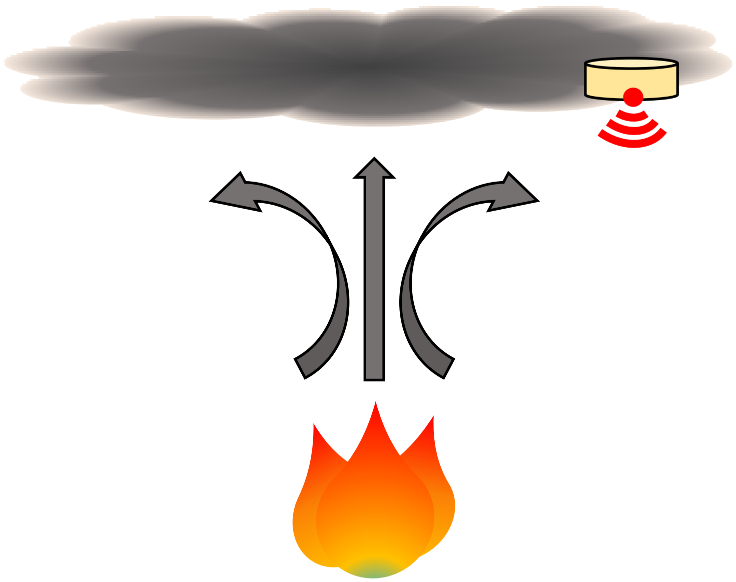
Smoke detector sensitivity standards

Different detectors are sensitive to different particle sizes!

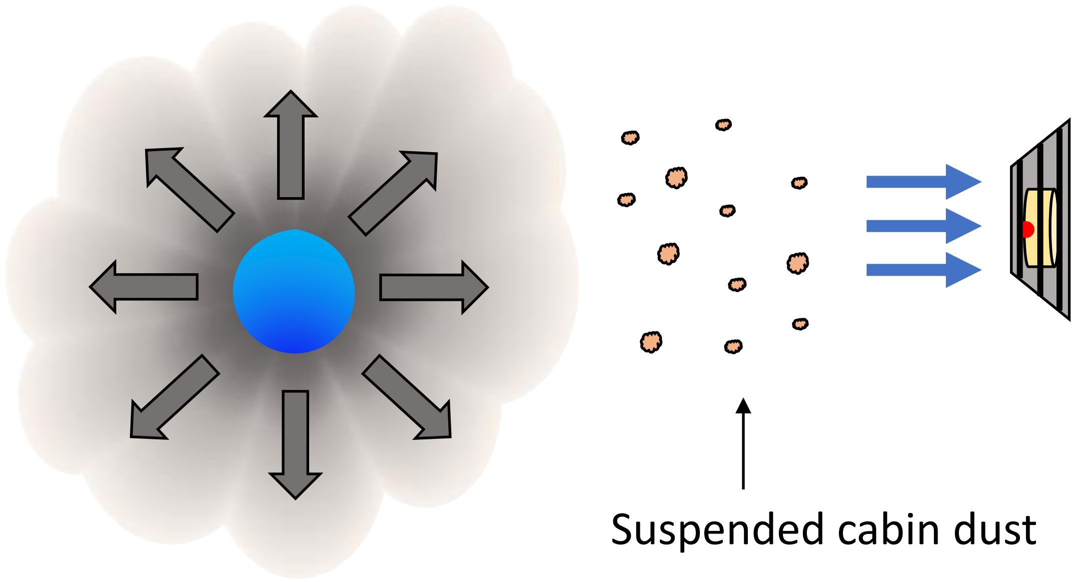
Spacecraft Smoke Detection Challenges

- In microgravity, **no buoyancy** → plume does not rise to ceiling
- **How much smoke needs to be produced** to reach detector alarm thresholds?

Earth Gravity



Microgravity



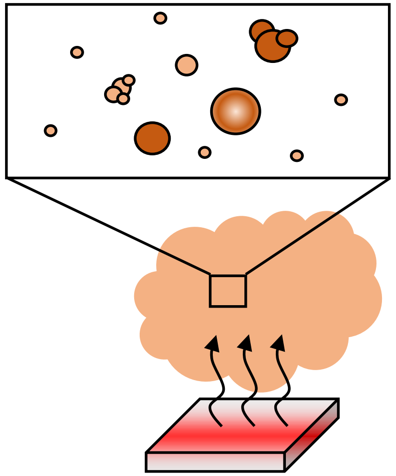
Urban et al., 46th Int. Conf. Environ. Sys., Vienna, Austria, ICES-2016-318, July 2016.

The Smoke Aerosol Measurement Experiment (SAME)

SAME = First major effort to characterize smoke from early-stage microgravity fires!

- Target particles from **oxidative pyrolysis** rather than flaming combustion
- **Identify relevant particle sizes/morphologies** from spacecraft-relevant fuels
- **Evaluate detector performance** for these particles

Image credit: NASA, SAME experiments, grc.nasa.gov/space/iss-research/msg/same/#lightbox-gallery-1-2



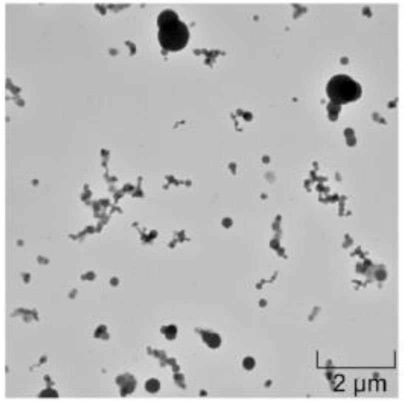
SAME Publications:

- *Urban et al., 070FR-0171, 8th U. S. National Combustion Meeting, Salt Lake City, UT, May 2013.*
- *Meyer et al., Aerosol Sci. Tech., 49:5, 299-309, 2015.*
- *Mulholland et al., Aerosol Sci. Tech., 49:310–321, 2015.*
- *Meyer et al., Fire Safety Journal, 98. 74-81, 2018.*

Summary of SAME Results

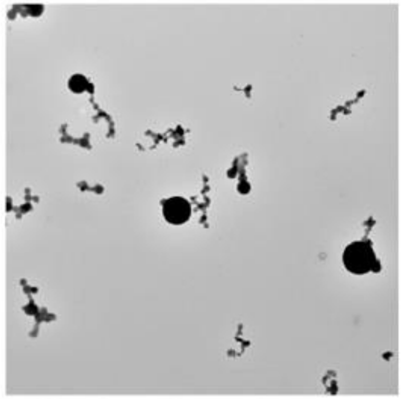
- “Aging” occurs over time scales relevant to detection
- Below a flow threshold, air flow influences smoke particle size
- Detector response dependent on particle size and detection mechanism:
  - ISS forward light scattering detector had diminished response to smallest particles
  - Space shuttle ionization detector had slightly better response to smallest particles
  - **“One size fits all” detector does not exist!**

Unaged

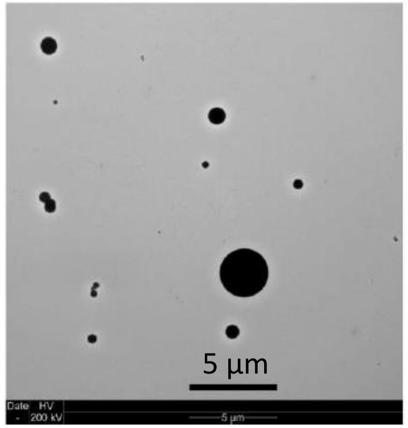


+12 min

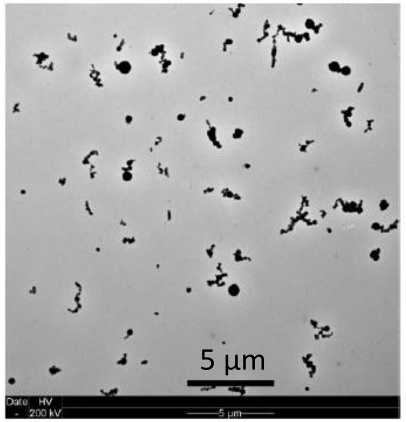
Aged ~12 min



Air flow = 0 cm s^{-1}



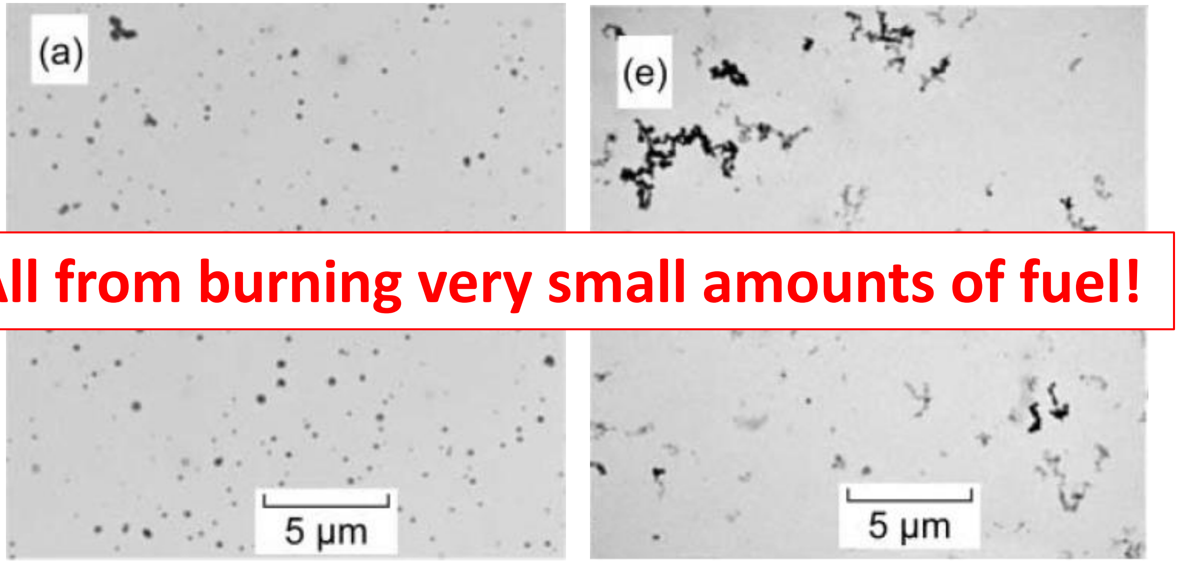
Air flow = 8 cm s^{-1}



Summary of Detection Challenges

1. Different smoke detector designs are biased towards **different particle sizes**
2. Particle sizes/morphologies vary by **fuel type and oxidative pyrolysis conditions**
3. Particles can **grow/evolve over time** depending on flow conditions

Kapton (ox. pyrolysis) Teflon (ox. pyrolysis)



All from burning very small amounts of fuel!

- Need for **particle size/morphology** measurements from large-scale flaming combustion in microgravity
- Need for **"emission factors"** (amount of smoke produced relative to amount of fuel burned) to improve models for predicting fire outcomes and smoke transport

Meyer et al., Aerosol Sci. Tech., 49, 5, 299-309, 2015.
Meyer et al., Fire Safety Journal, 98, 74-81, 2018.

Spacecraft Fire Safety (Saffire) Experiments

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; S-VI TBD):
  - In addition to flame properties, measure **combustion products from variety of fuels**
  - **Test novel post-fire cleanup technology: "Smoke Eater"**

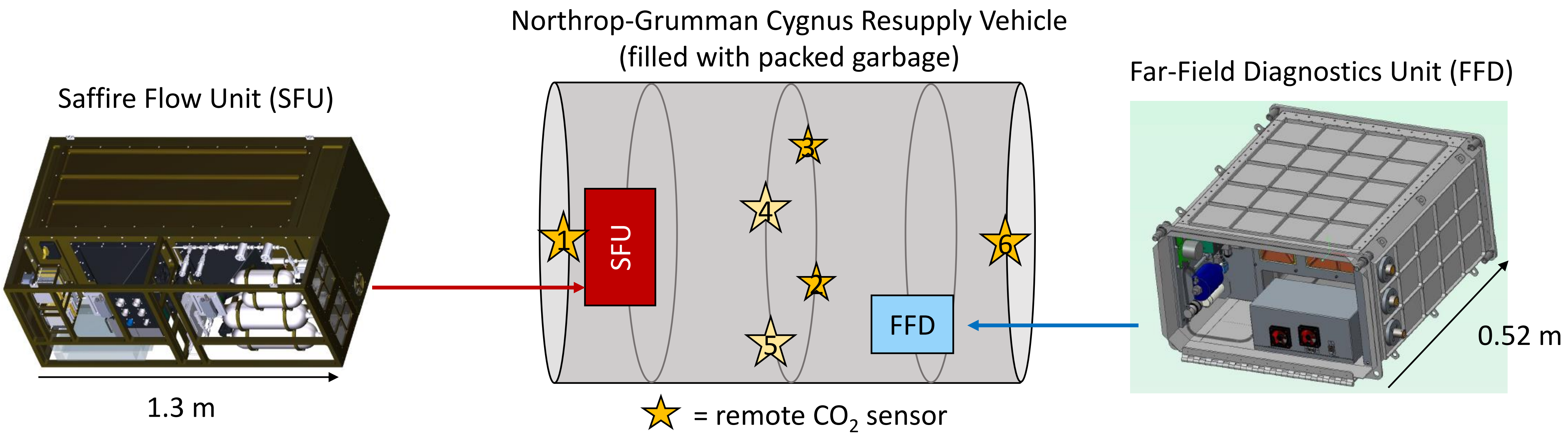
nasa.gov/feature/northrop-grumman-cygnus-launches-arrivals-and-departures/

Image credits: NASA

Ruff and Urban, 46th Int. Conf. Environ. Sys., Vienna, Austria, ICES-2016-428, July 2016.

Saffire-IV and V Experiment Description

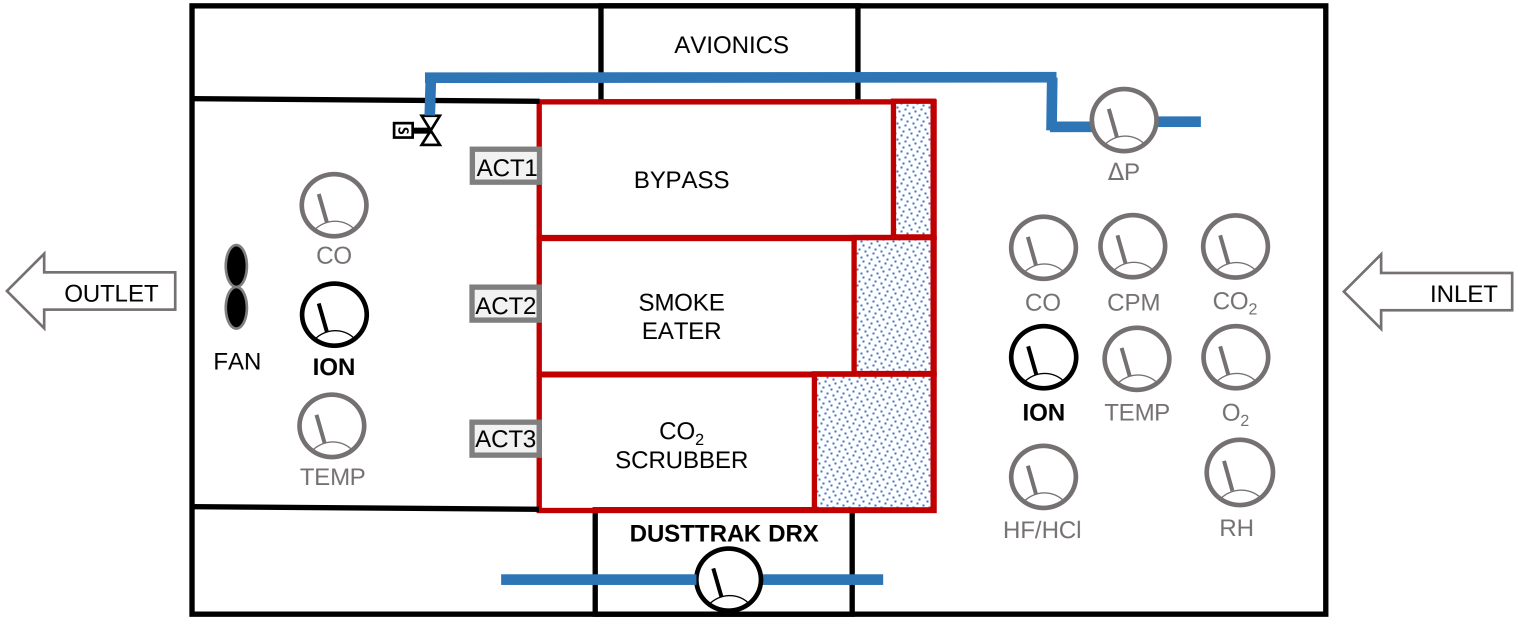
- Fire experiments housed within the Saffire Flow Unit (SFU)
- Plume transport through cabin tracked by remote CO_2 sensors
- Far-field diagnostics (FFD) unit located at the opposite end of the cabin from the SFU
- Materials tested: cotton/fiberglass blend (“SIBAL”), cotton jersey, PMMA (one-sided, two-sided, structured)

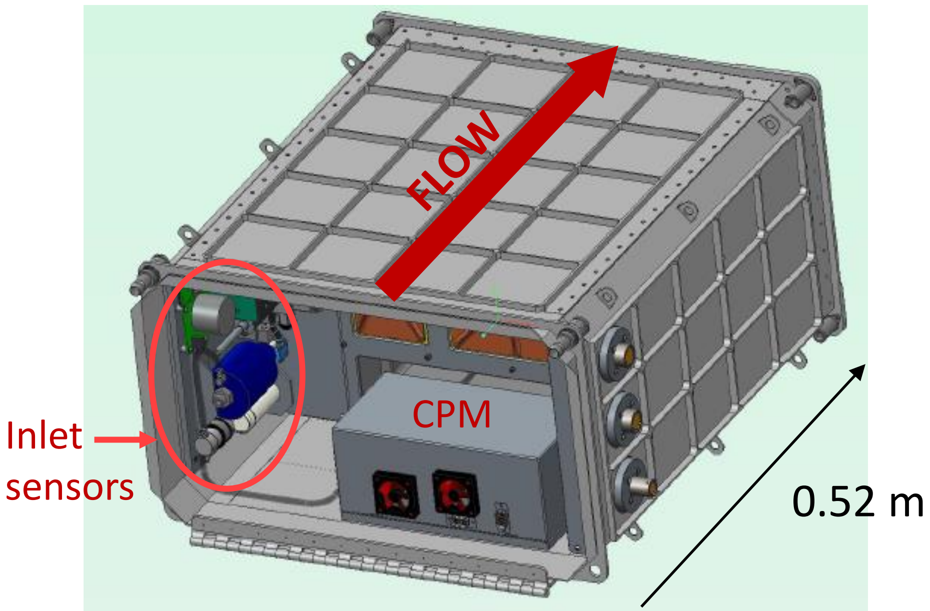


Urban et al., “Preliminary Results from Saffire IV and V Experiments on Large Scale Spacecraft Fires,” 50th Int. Conf. Environ. Sys., ICES-2021-266, July 2021.

The Far-Field Diagnostics Unit (FFD)

- Three main flow paths: CO_2 scrubber, smoke eater, and bypass
- Gas sensors: CO, CO_2, acid gas (HF/HCl), Combustion Products Monitor (CPM: CO, CO_2, HF, HCl, H_2O, O_2; Vista Photonics)
- **Particle measurements: DustTrak DRX (TSI, Inc.), ionization smoke detectors (First Alert)**



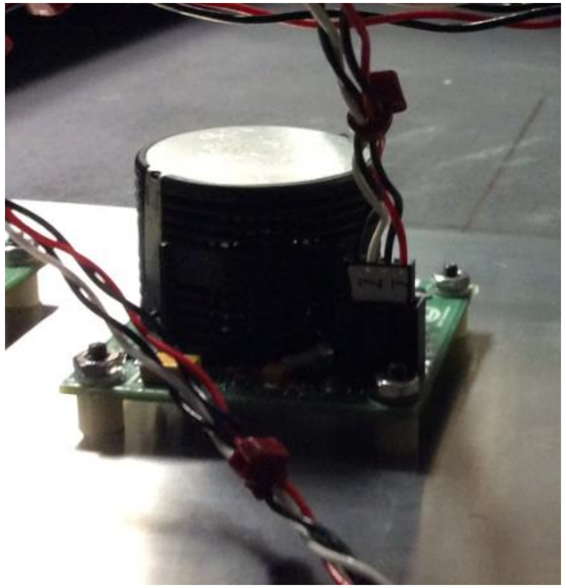


Particle Instrumentation

DustTrak DRX (Model 8533, TSI, Inc.)

- Combination of photometry (measurement of particle ensemble) and single-particle counting
- Provides **particle mass concentrations (mg m^{-3})** for five size ranges: PM_1, $PM_{2.5}$, PM_4, PM_{10}, total mass concentration
- Wang et al., Aerosol Sci. Tech., 43:939-950, 2009

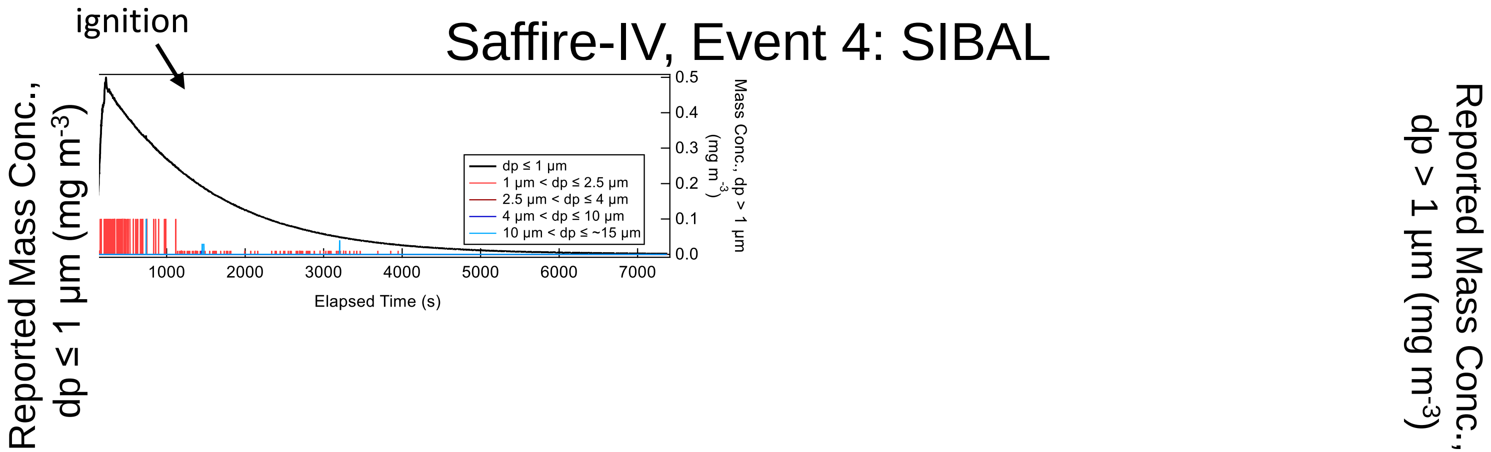
Ionization Chamber (First Alert)

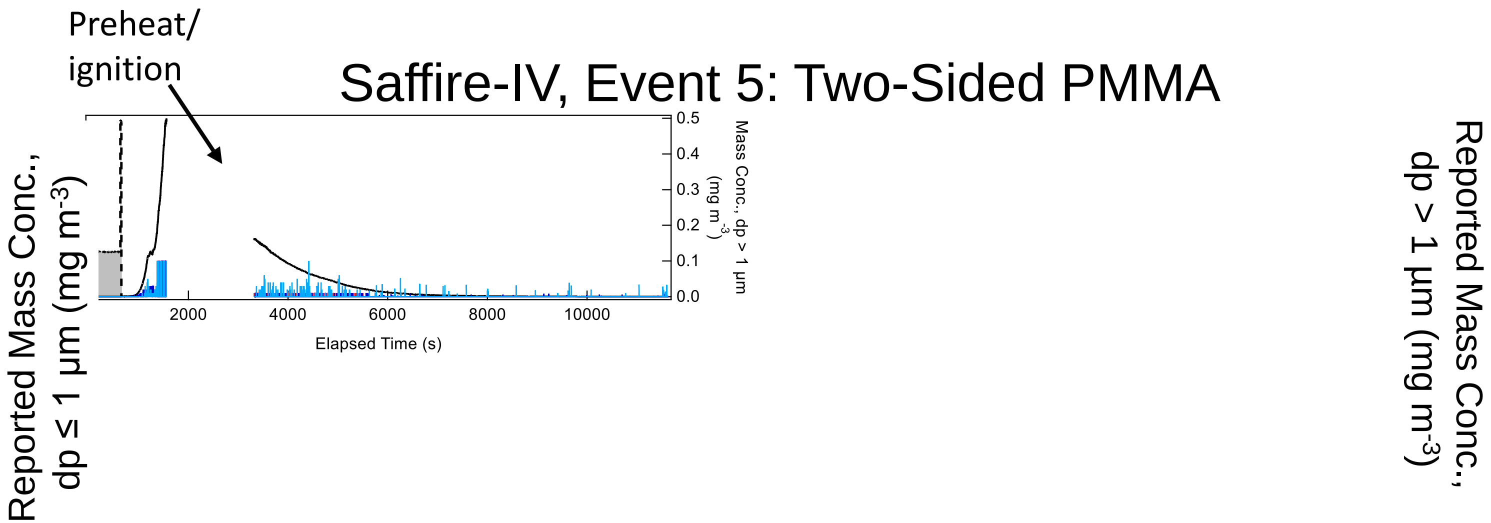


- Chambers modified/ rehoused from a commercial device
- Approximately proportional to **aerosol diameter concentration (mm cm^{-3})**: average d_p × total number concentration
- Placed at inlet and outlet of FFD to evaluate smoke eater filtration capability

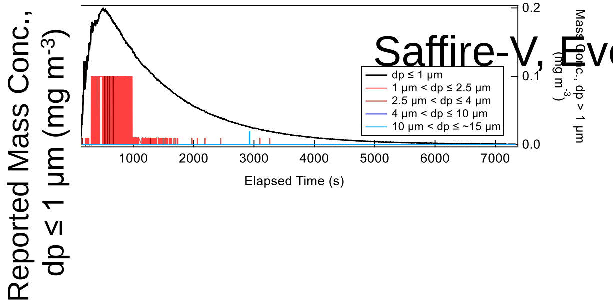
Saffire-IV Particle Mass Distributions

- Particle mass concentration **dominated by submicron particles** (PM_1) in all five burn events
- PMMA event produced **higher concentrations of larger particles (d_p > 4 µm)** compared to SIBAL (cotton/fiberglass blend)
- Avionics temperatures and images indicate clogging of SFU outlet screen – **FFD measurements likely missed a significant fraction of larger particles**

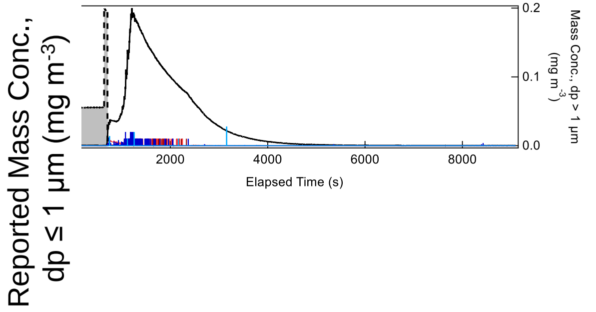




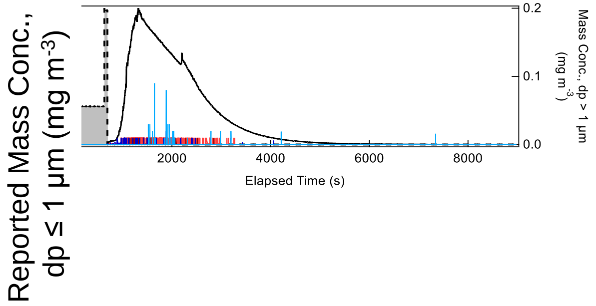
Saffire-V Particle Mass Distributions



Saffire-V, Event 5: Cotton Jersey



Saffire-V, Event 6: One-Sided PMMA



Saffire-V, Event 8: Structured PMMA

- As in Saffire-IV, particle mass concentration **dominated by submicron particles** (PM_1) in all five burn events
- PMMA events produced **higher concentrations of larger particles (d_p > 4 µm)** compared to cotton jersey

What can we do with Saffire measurements?

- **Goal:** relate mass concentration measurements to detection readings (e.g., obscuration)
- **Major challenge:** Detection methods depend on aerosol properties (size, shape, optical parameters)

Future Fire Safety 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 µm) 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**

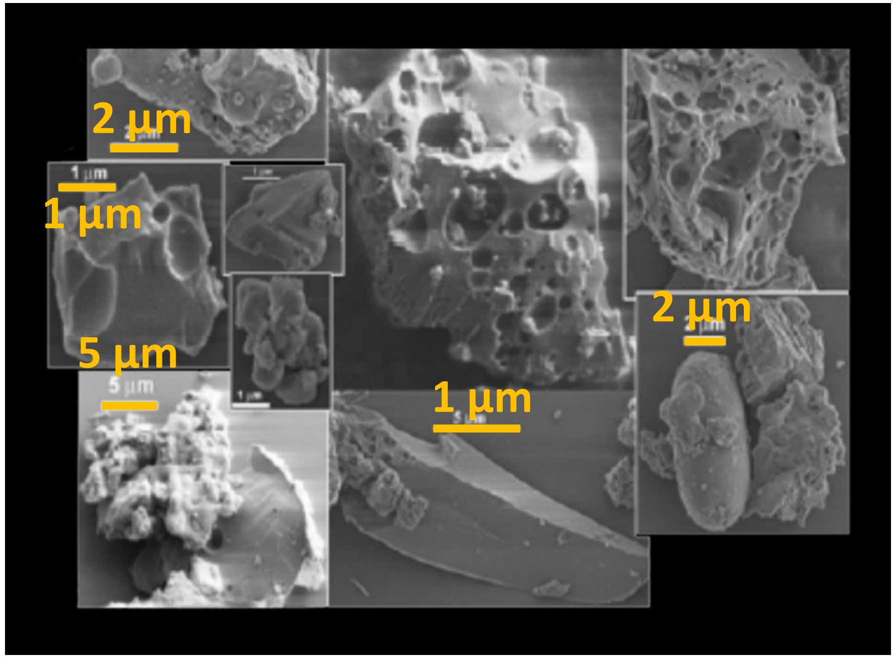


Image credit: NASA. nasa.gov/exploration/humanresearch/multimedia/images/hrpg_img_05.html.

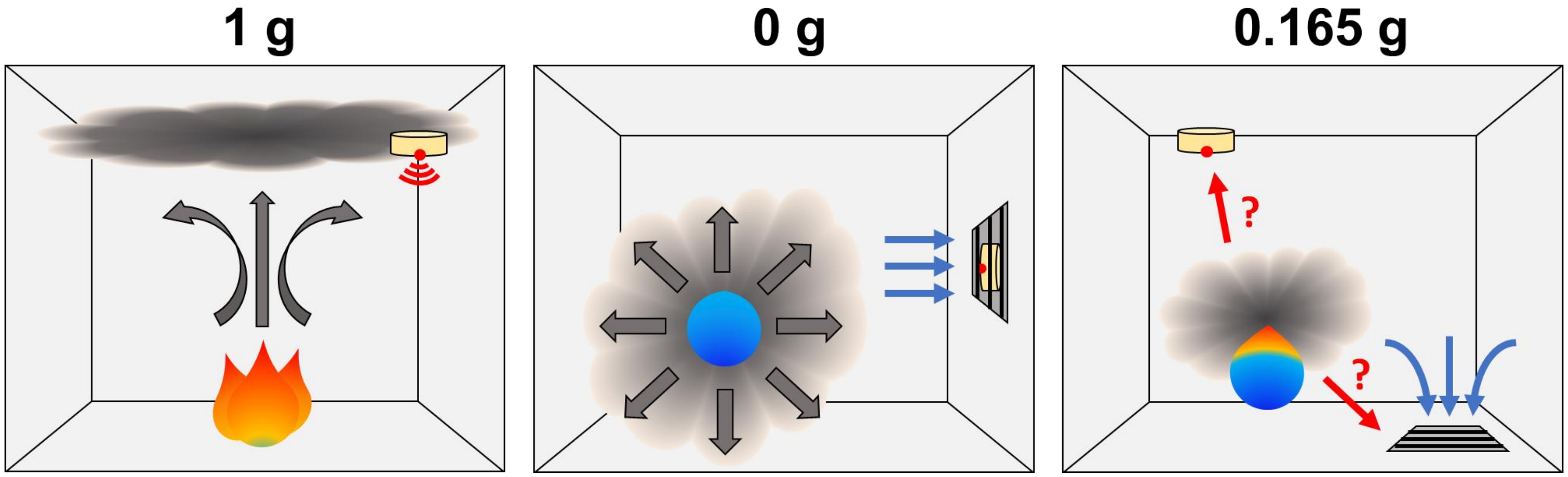
Future Fire Safety Challenges: Lunar Missions

- 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.

Image credit: NASA, Artemis Lunar Exploration Program Overview
nasa.gov/specials/artemis/

Ruff et al., Int. Conf. Environ. Sys., ICES-2020-173, 2020.
Sacksteder and T'ien, 25th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1685-1692, 1994

Future Fire Safety Challenges: Lunar Missions



- How can we design an optimal detector for a lunar habitat? Martian habitat?
- How much does buoyancy contribute to plume transport in lunar gravity? Does smoke rise to the ceiling even if air returns are on the floor?

Acknowledgements

- Saffire FFD analysis coauthors: Michael Casteel, John Graf, John Easton, Justin Niehaus, **Marit Meyer**, Gary Ruff, David Urban
- International Saffire Science Team
- ZIN Technologies Saffire team
- Universities Space Research Association (USRA) Glenn Engineering and Research Support Contract No. 80GRC020D0003
- Dr. Carol Kory
- Advanced Exploration Systems Life Support Systems Project