Spacecraft Fire Safety Research
NASA Glenn Research Center

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**Aerosols** are tiny particles suspended in the air.

Aerosols in Earth's atmosphere include pollution, *smoke*, dust, pollen as well as particles from many other natural and man-made materials.

*We breathe in aerosols all day long.*
1 nanometer is a billionth of a meter
I overheat materials to make smoke...

Called *pyrolysis* (like smoldering)

--No flames (no combustion)

When smoke is concentrated, it ‘*ages*’

--individual particles stick together

= *agglomeration*
Fire Facts

• Almost 20% of home fire deaths resulted from fires beginning with upholstered furniture
• Over 40% of home fires are caused by cooking equipment
• Fire safety systems here on Earth have been developed based on extensive study of typical fires
  • Established body of research characterizes smoke from building fires and forest fires (flaming combustion)
• Current fire detection systems in space were developed without spacecraft fire data
  • International Space Station has no cooking, no couches that can catch on fire
  • A need existed for a comprehensive study of smoke from typical spacecraft materials

Outline

• Background Information
  • Fire and Spacecraft
  • Smoke Aerosol Measurement Experiment (SAME)

• Smoke-in-drums Experiment

• GASP laboratory study on early smoke detection

• Morphology of selected smoke particles

• SAFFIRE Experiment
Fire in Space

- Materials in spacecraft are non-flammable, but can still overheat and smoke
- With the absence of gravity smoke does not rise
- Most likely source of a fire is overheating electronic equipment
- Goal: detect smoke before a flame develops
  - Research smoke from *pyrolysis*, not flames (combustion)
International Space Station
Destiny Module, a.k.a. U.S. Lab
Destiny Module, aka U.S. Lab

Clean air enters from ducts here

‘Dirty air’ pulled through HEPA filters here

Simulation results courtesy of John Brooker, ‘ISS Destiny Laboratory Smoke Detection Model,’ DOI: 10.4271/2007-01-3076
Destiny Module, a.k.a. U.S. Lab

Low-gravity

Normal-gravity

Simulation results courtesy of John Brooker, ‘ISS Destiny Laboratory Smoke Detection Model,’ DOI: 10.4271/2007-01-3076
Avoid false alarms:
Turn off smoke detectors while vacuuming
Smoke Aerosol Measurement Experiment (SAME)

- On ISS in 2007 and 2010
- Experiment designed to generate pyrolysis smoke in low gravity
  - Common spacecraft materials
  - Ability to concentrate and age smoke in space
  - Measure with small, cheap instruments
    - The best choices at the time
  - Collect smoke particles to bring back for microscopy
Smoke Aerosol Measurement Experiment (SAME)
SAME Spacecraft Materials

- **Pyrell®** (flame retardant polyurethane foam), used to cushion payloads during launch.
- Lamp wick (cellulose) represents clothing & paper.
- **Teflon®** is used in wire insulation, sampling bags, space suits & cargo liners.
- **Silicone rubber**, used in gaskets & adhesives.
- **Kapton® film**, a polyimide used for thin-film heaters, wire insulation, tape, space suits.
Microgravity Science Glovebox (MSG)
Ground Unit - SAME Hardware in MSG

- Aging Chamber
- Sample Diluter
- Instrument Boxes
- Tubing Bundle
- Data Acquisition and Control Unit
- Fluids Control Unit
- Sample Carousel
- Particle collector
SAME Smoke Particles from ISS

‘SAME’ as smoke on Earth!

scale bars = 2 μm
Smoke-in-drums Ground Experiment

• Goal
  • Make SAME smoke in a lab
  • Measure with returned ISS instruments—AND—a high fidelity reference instrument (which is too heavy and complex to fly)
• Dilute the smoke by sending it into a large 55 gallon drum
  • Stops coagulation (aging) of the smoke particles during measurements
Smoke-in-drums Experiment

SAME smoke generation hardware is ground engineering hardware (identical to ISS setup)

Instruments are units returned from ISS

Diagram showing the flow of smoke and air through the system, with labels for each component:
- To piston air/vacuum controller
- Air piston
- Valves
- Sample carousel
- Smoke generation duct
- Thermal precipitator
- Diluter
- P-Trak®
- N₂ bottle
- Dust Trak®
- Ionization detector
- Plenum
- Orifice
- Filter
- 4-way crossover valve
- 55 gallon drum (Aged smoke)
- 55 gallon drum (Unaged smoke)
- SMPS
- Vacuum pump

PS-01155-1
Smoke-in-Drums Experiment

SAME engineering HW makes smoke

Small instruments returned from ISS

Reference instrument

Two drums for aged & unaged smoke

Hood for purged smoke
Compare Particle Size Distribution: Pyrell

- ISS flight, 242 °C
- Smoke-in-drums, 234 °C
Gases and Aerosols from Smoldering Polymers (GASP) Laboratory

- Two vented enclosures cover all instruments
- Tube furnace heats materials in a ceramic 'boat'
- Safety permit = 1.5 years
One Recent GASP Experiment

• Test a miniaturized particle sensor for early detection of smoke from spacecraft materials
  • Compact Optical Dust Sensor (COTS)
    • Has potential for use in spacecraft fire detection?
    • Output response correlated to aerosol mass concentration for incense smoke (Yang et al. 2015)

4.6 cm x 3 cm, 16 g

COTS=Commercial-off-the-shelf
GASP Fuels

Nomex, a heat and flame-resistant woven textile, used for acoustic insulation, cargo bags, thermal blankets & pressure suits
Components: several thin film resistors, a tantalum capacitor, an inductor and a resin-encapsulated LED with the leads removed
GASP Experiments: Early Fire Detection

Detection times from 1 minute to 6 minutes (Teflon is infinity)  
Too slow!

PCB is ‘printed circuit board’ (bare FR-4)
Circuit board & Components

Images and microscopy data courtesy of RJ Lee Group
Circuit board & Components

Crustal particle

Microscopy courtesy of RJ Lee Group
Wire Insulation Smoke Particles
(partially fluorinated polyimide, PFPI)

Crystalline particles

Images courtesy of RJ Victoria Bryg/NSCER
Teflon Smoke Particles

Images courtesy of RJ Lee Group and Victoria Bryg/NSCER
Kapton Smoke Particles

- Thermal decomposition of Kapton results in liquid aromatic products
- The general spherical shape of the particles observed is consistent with the particles starting as a liquid solution with many components
- Chain-like agglomerates, 100 to 350 nm primaries

Images courtesy of RJ Lee Group and Victoria Bryg/NCSER
Nomex Char Particles

Microscopy courtesy of RJ Lee Group
Nomex Tar Balls

Images courtesy of RJ Lee Group
We need a ‘big burn’!

• Past NASA combustion research
  • Burning 3mm fuel droplets
  • Small samples

Most U.S. agencies responsible for large transportation systems conduct full-scale fire tests
SAFFIRE: Spacecraft Fire Safety Demonstration

• Use a disposable cargo vehicle for a fire experiment just before de-orbit and destruction

• SAFFIRE I, II, III
  • Orbital Cygnus vehicle

• SAFFIRE IV, V, VI
  • SpaceX Dragon vehicle
SAFFIRE: Spacecraft Fire Safety Demonstration

The video below can be found at: https://www.youtube.com/watch?v=0JkQ12JluJ0
Summary

• Ongoing work at NASA Glenn Research Center is performed to characterize smoke aerosols for improving spacecraft fire safety
  • Oxidative pyrolysis experiments
  • Variables affecting smoke production
    • Database of spacecraft smoke properties
      • Detection
      • Post-fire cleanup
  • SAFFIRE
    • Tests 1 through 3 –combustion emphasis
    • Tests 4 through 6 –smoke detection emphasis
      • GASP lab will support with fuel experiments and instrument down-selection
      • New smoke ‘room’ under construction at Glenn
Questions?
Other Fire Research at NASA Glenn Research Center

**Why Study Combustion in Reduced Gravity?**
- To enable space exploration
- To advance science
- To enable technologies on earth

**The Combustion Integrated Rack (CIR) is an ISS Rack in the Destiny module dedicated to combustion research on the ISS**
- Study combustion in a range of ambient environments
- Study liquid, gaseous and solid fuel combustion
- Modular and upgradeable to improve capabilities as technologies mature
- Capable of remote, nearly autonomous operation

**The ISS Experiment manifest**
- Solid Combustion – SoFIE (2019 – 2020)

**Flame Extinguishment Experiment (FLEX) results revealed a unique two-stage burning event:** Cool Flames
- Hot flame radiatively extinguishes -> initiates cool flame burning
- Observation not possible without long-duration microgravity
- Originally thought to be ‘impossible’
- Near-term applications to new engine (e.g., HCCI) technologies - lower emissions and higher efficiencies
- Spacecraft safety procedures based only on considerations of hot flames may be inadequate for assuring safety under all conditions.
Links for more Saffire information

- [http://m.voanews.com/a/nasa-plans-to-light-large-fire-in-space/3240548.html](http://m.voanews.com/a/nasa-plans-to-light-large-fire-in-space/3240548.html)
- [http://www.computerworld.com/article/3044797/space-technology/nasa-intends-to-start-a-large-scale-fire-in-space.html#tk.rss_all](http://www.computerworld.com/article/3044797/space-technology/nasa-intends-to-start-a-large-scale-fire-in-space.html#tk.rss_all) (Quotes Astronaut Dan Tani and also links to Saffire animation video)
- [https://www.rt.com/usa/335874-nasa-fire-space-cygnus/](https://www.rt.com/usa/335874-nasa-fire-space-cygnus/) (Another link to Saffire video)
Smoke Characterization and Feasibility of the Moment Method for Spacecraft Fire Detection

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INTRODUCTION

SAME Experiment

Appropriate design of fire detection systems requires knowledge of both the expected signature of the events to be detected and the background levels. Ambient aerosols in spacecraft include significantly larger particles than on the Earth, as gravitational settling is absent; consequently, smoke detectors must optimally distinguish between background aerosols and smoke in order to prevent false alarms. Terrestrial
**Fire Basics**

Diffusion flame: fuel is on one side and the oxidizer is on the other side. Examples are forest fires, a candle flame, industrial scale furnace and a flame spreading across a piece of paper.
What makes a fire grow or die?

**Heat Generation Rate** > **Heat Loss Rate**: Fire persists

**Heat Generation Rate** < **Heat Loss Rate**: Extinguishes

**Heat Generation Rate**
- Concentration of Fuel, Concentration of Oxygen, Temperature (exponential dependence), Pressure, Type of fuel

**Heat Loss Rate**
- Radiation, Conduction, Convection – all functions of temperature difference between fire and surroundings

To first order, gravity affects the rate of supply of oxygen and rate of convective loss of heat...

...but there are lots of other effects
Microgravity Behavior

Lower temperature, but it melts faster... it doesn’t drip...