Spacecraft Fire Safety Research
NASA Glenn Research Center

By
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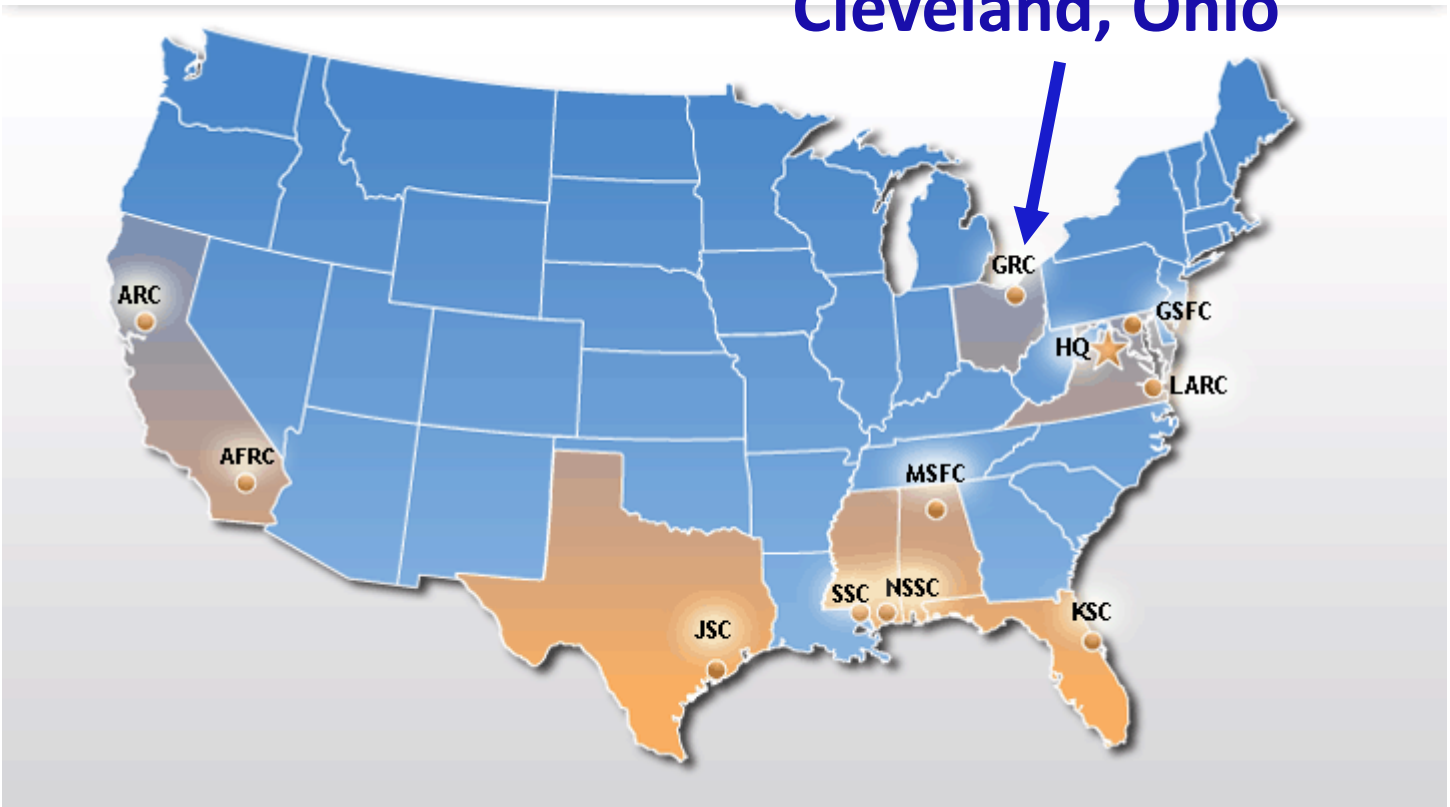
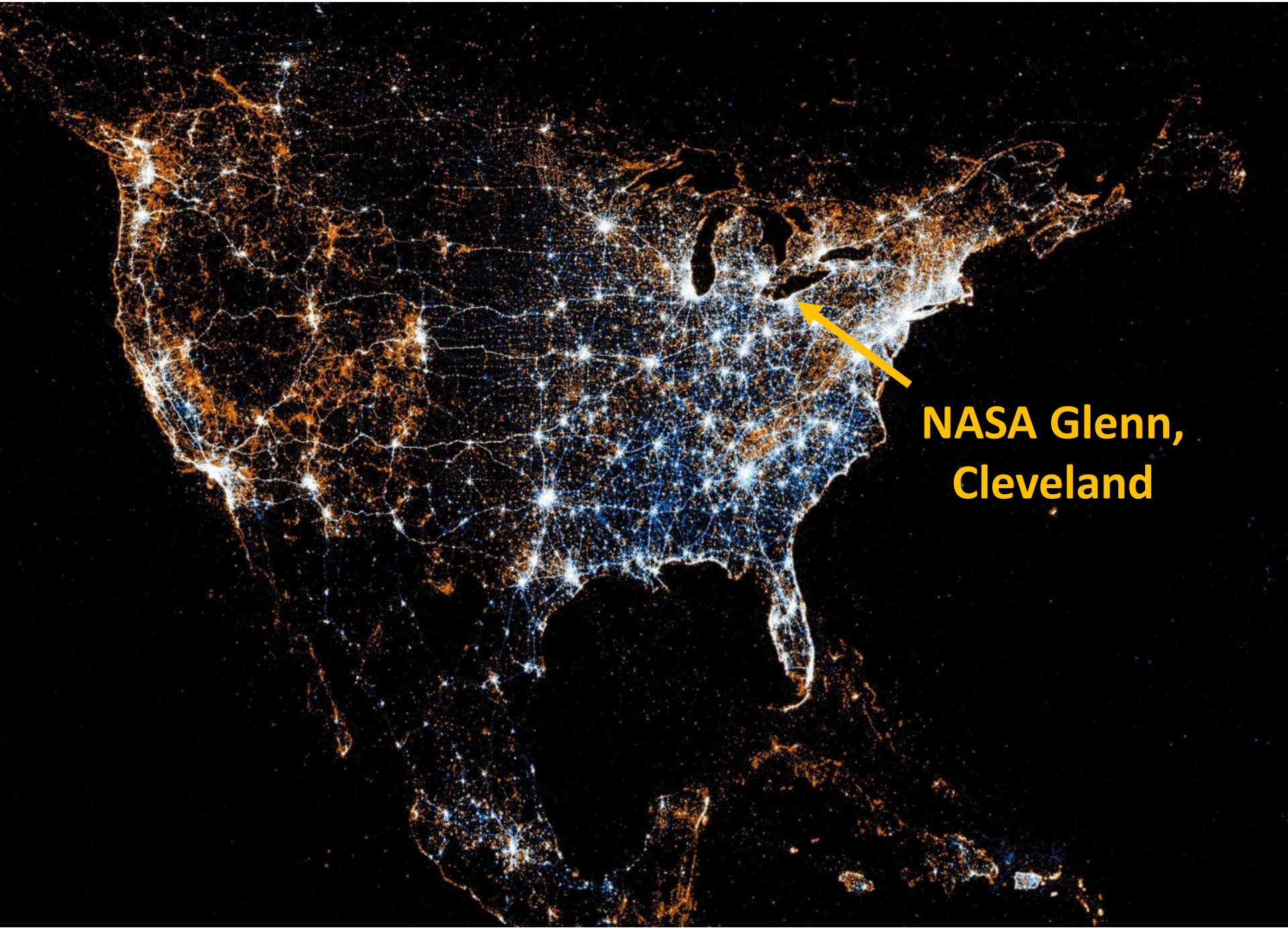
NASA Glenn Research Center
Cleveland, Ohio

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Jargon Spacecraft Fire Safety terms

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.

Jargon Spacecraft Fire Safety terms

1 nanometer is a billionth of a meter

Jargon Spacecraft Fire Safety terms

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

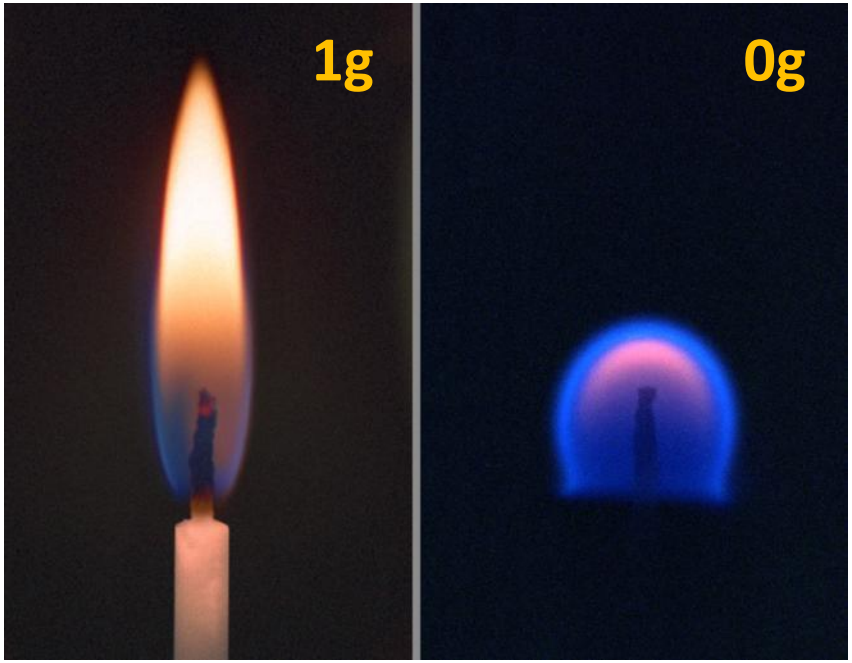
- Almost 20% of home fire deaths resulted from fires beginning with upholstered furniture
- Over 40% of home fires are caused by cooking equipment
- Fire safety systems here on Earth have been developed based on extensive study of typical fires
  - Established body of research characterizes smoke from 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***

Statistics source: National Fire Protection Association (NFPA) Fire Analysis and Research Fact Sheet, April 2013.

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

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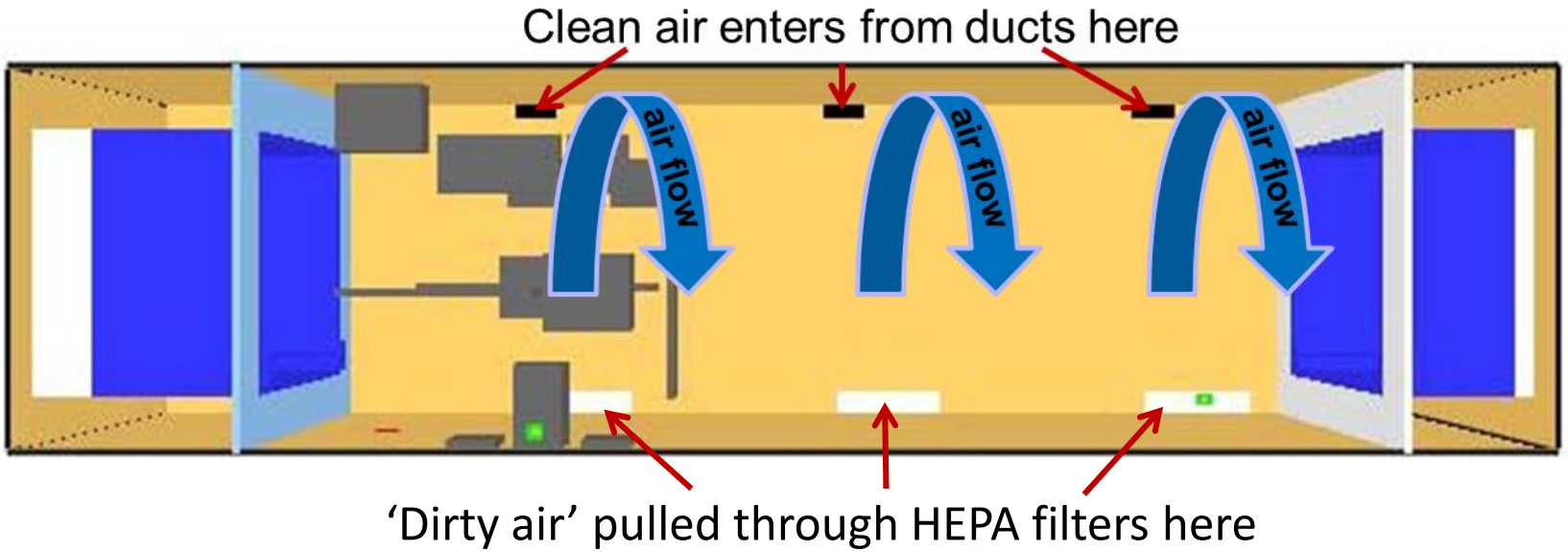
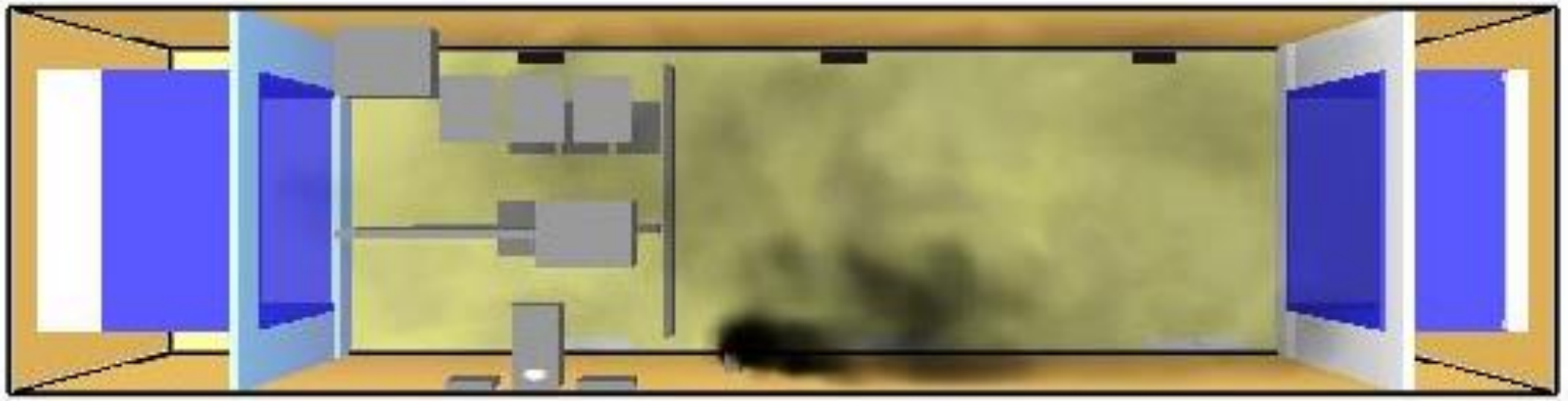
Destiny Module, aka U.S. Lab

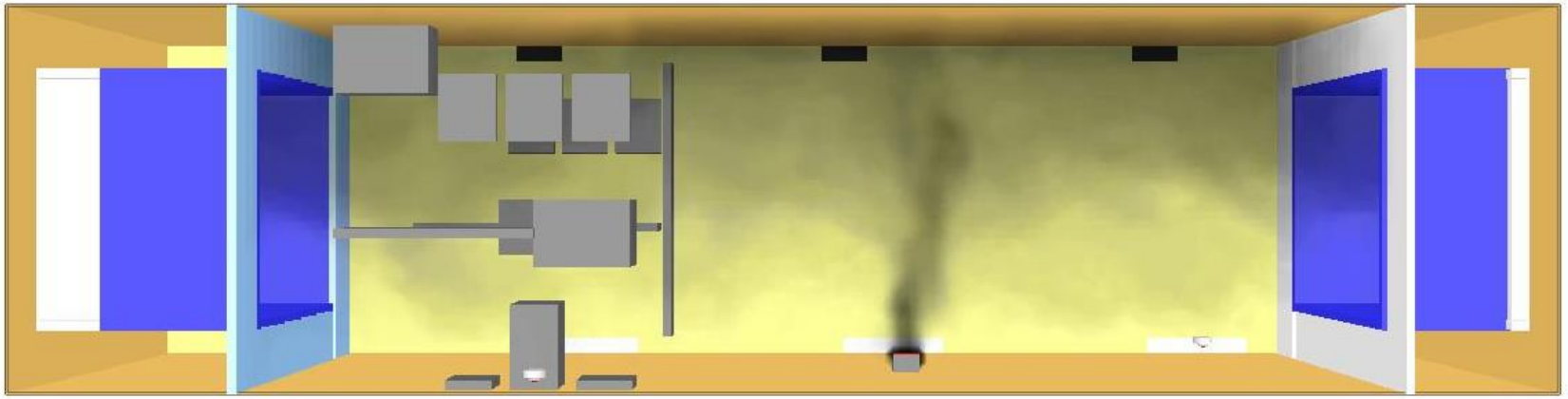


Simulation results courtesy of John Brooker, 'ISS Destiny Laboratory Smoke Detection Model,' DOI: 10.4271/2007-01-3076

Destiny Module, a.k.a. U.S. Lab



Low-gravity



Normal-gravity

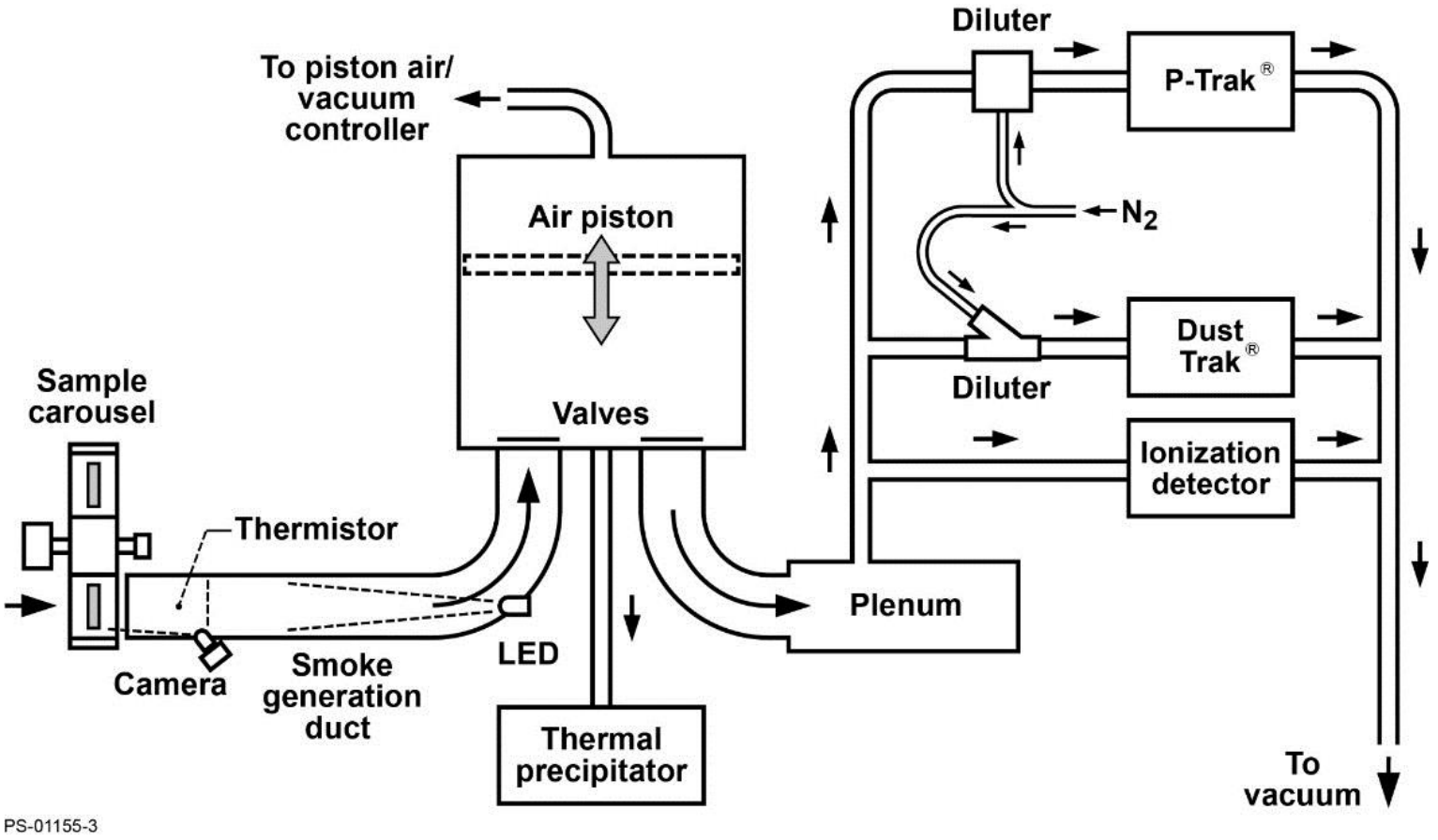
Simulation results courtesy of John Brooker, 'ISS Destiny Laboratory Smoke Detection Model,' DOI: 10.4271/2007-01-3076

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

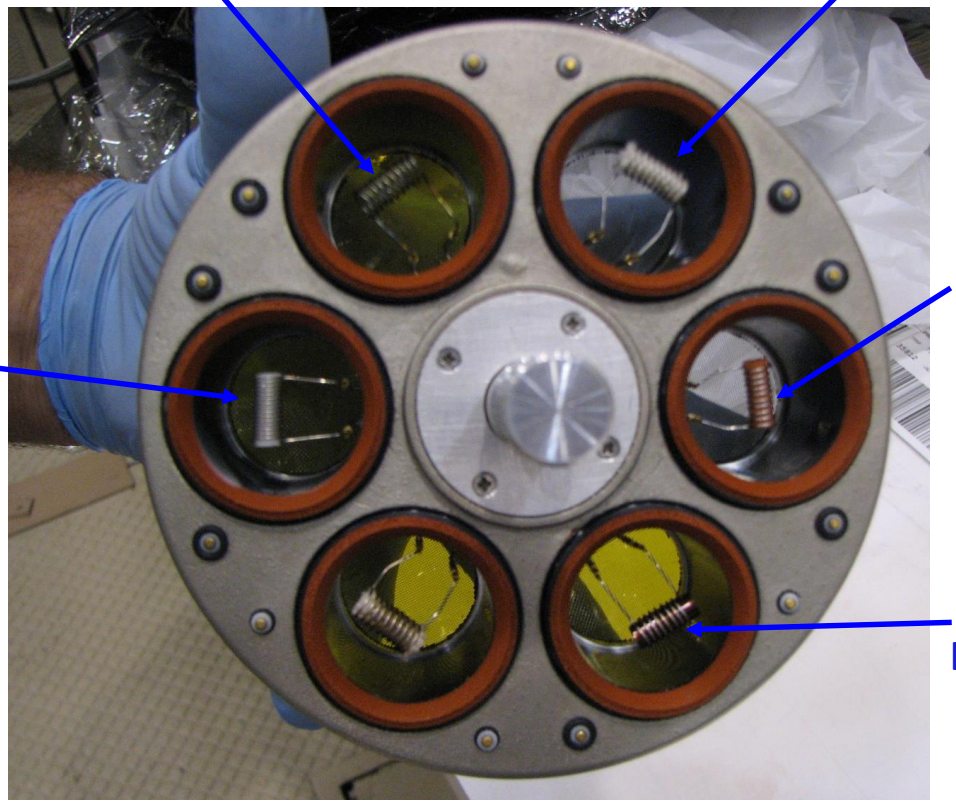
Smoke Aerosol Measurement Experiment (SAME)



SAME Spacecraft Materials

Pyrell® (flame retardant polyurethane foam), used to cushion payloads during launch

Lamp wick (cellulose) represents clothing & paper

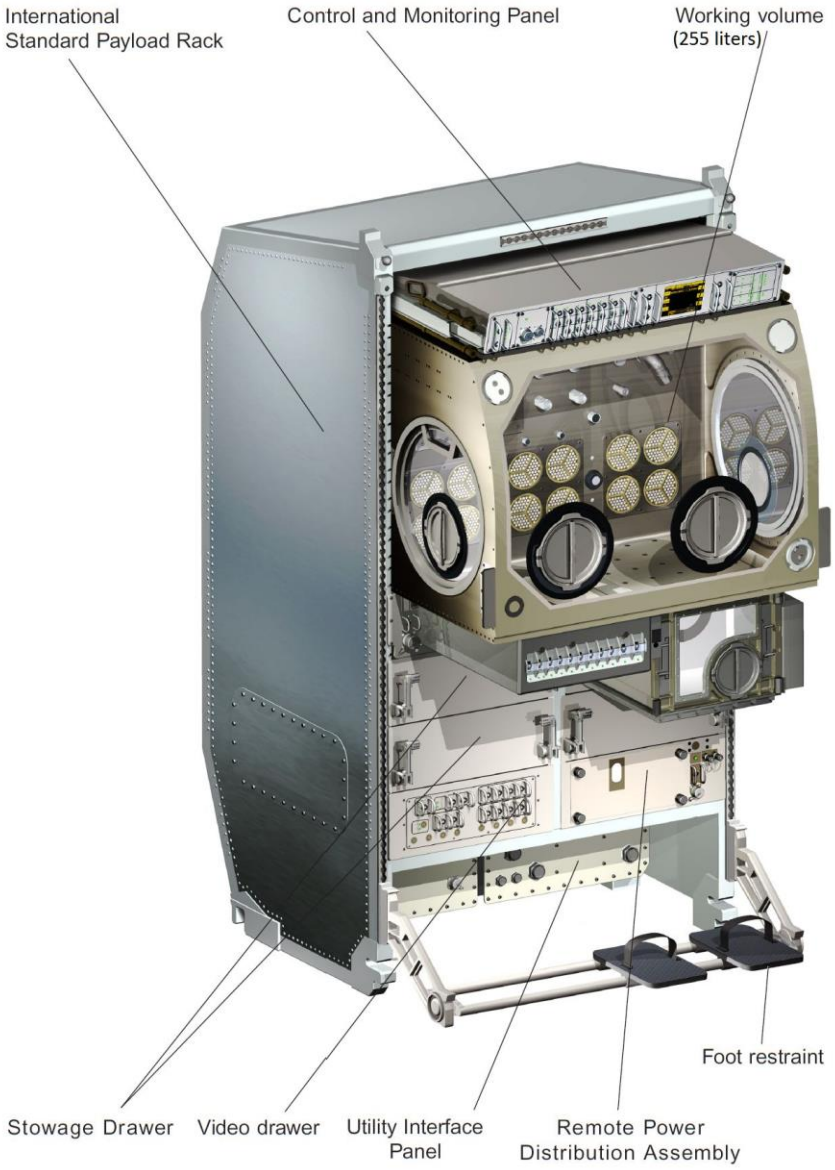


Teflon® is used in wire insulation, sampling bags, space suits & cargo liners

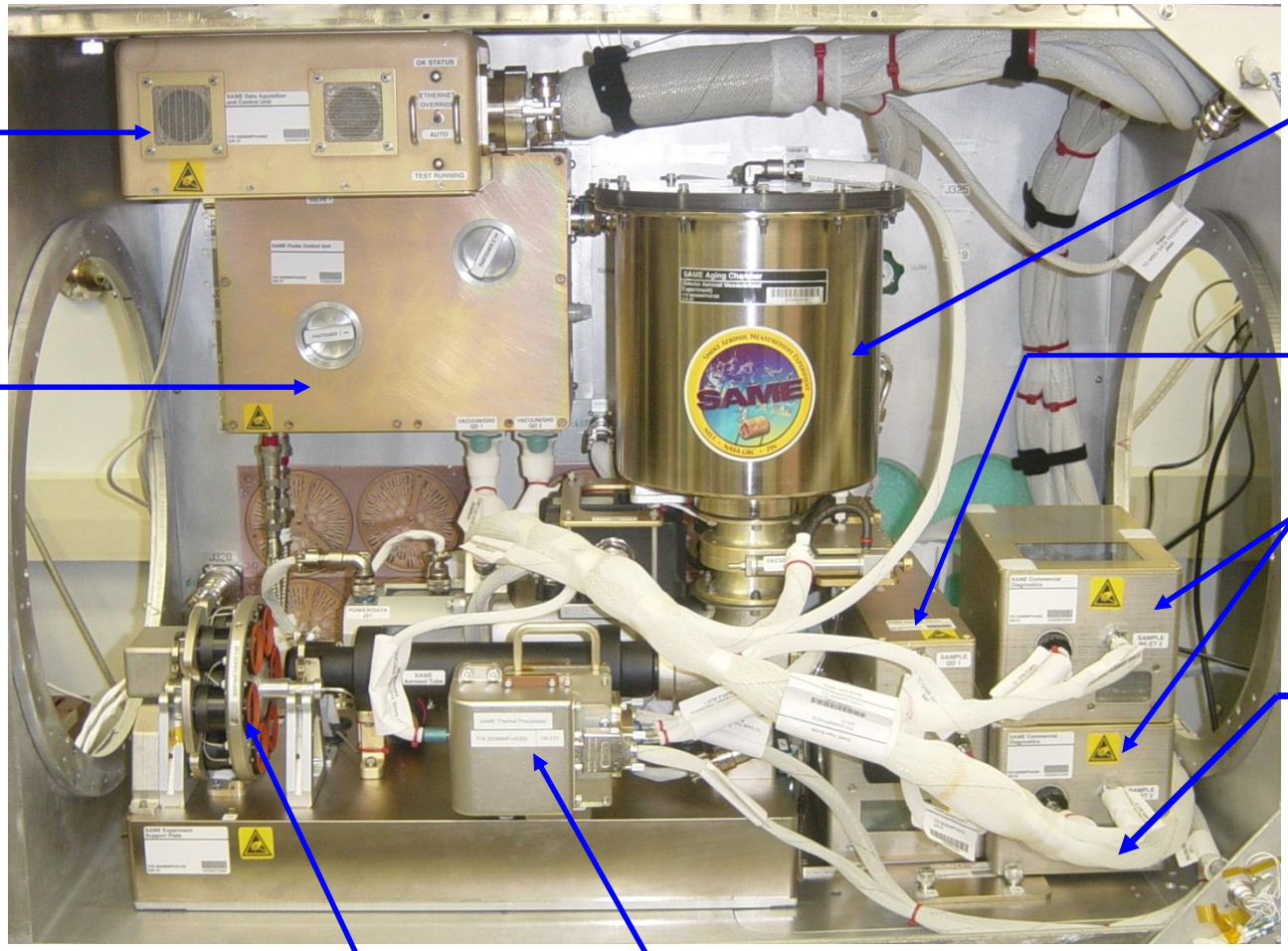
Silicone rubber, used in gaskets & adhesives

Kapton® film, a polyimide used for thin-film heaters, wire insulation, tape, space suits

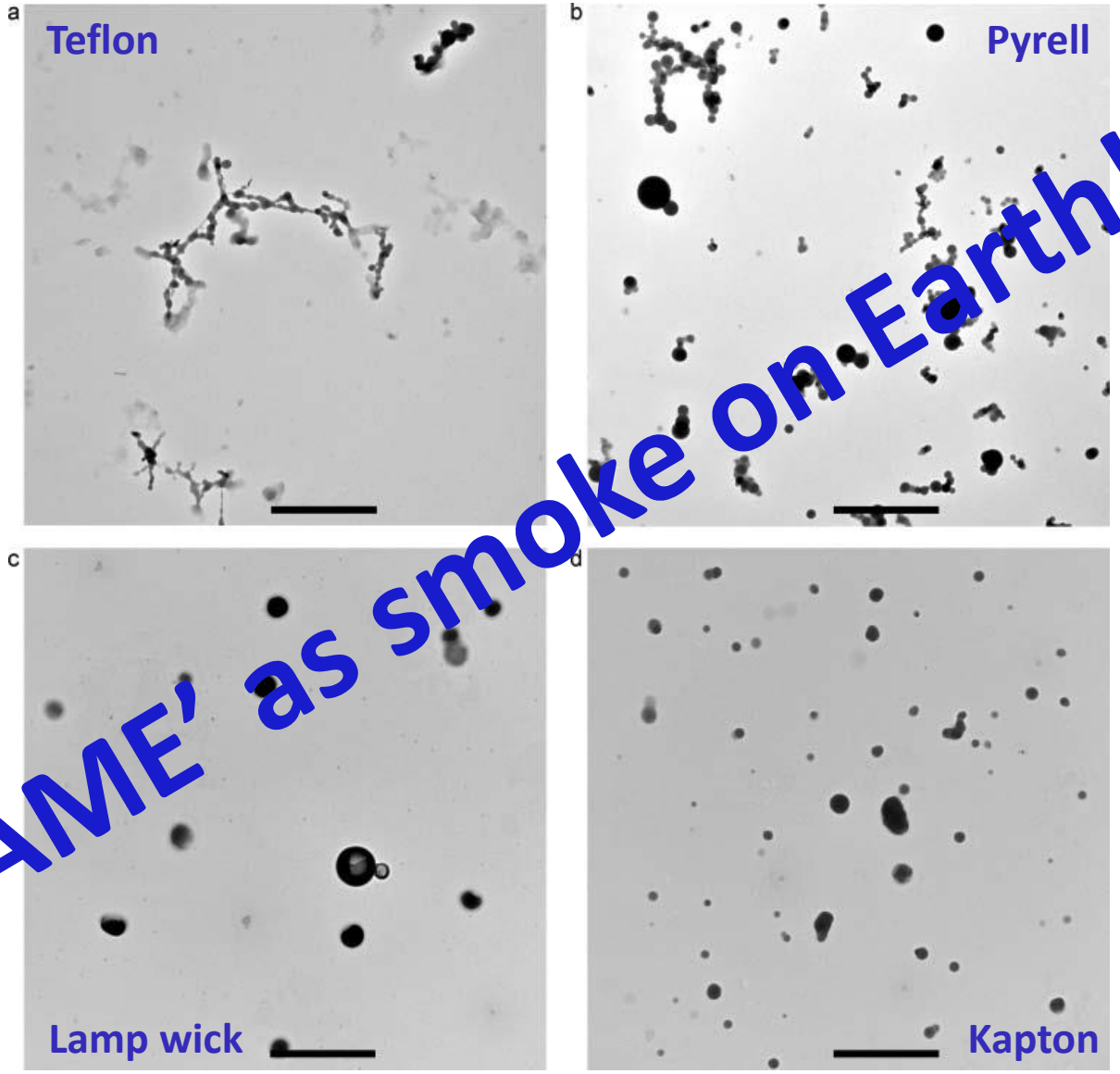
Microgravity Science Glovebox (MSG)



Ground Unit - SAME Hardware in MSG



SAME Smoke Particles from ISS



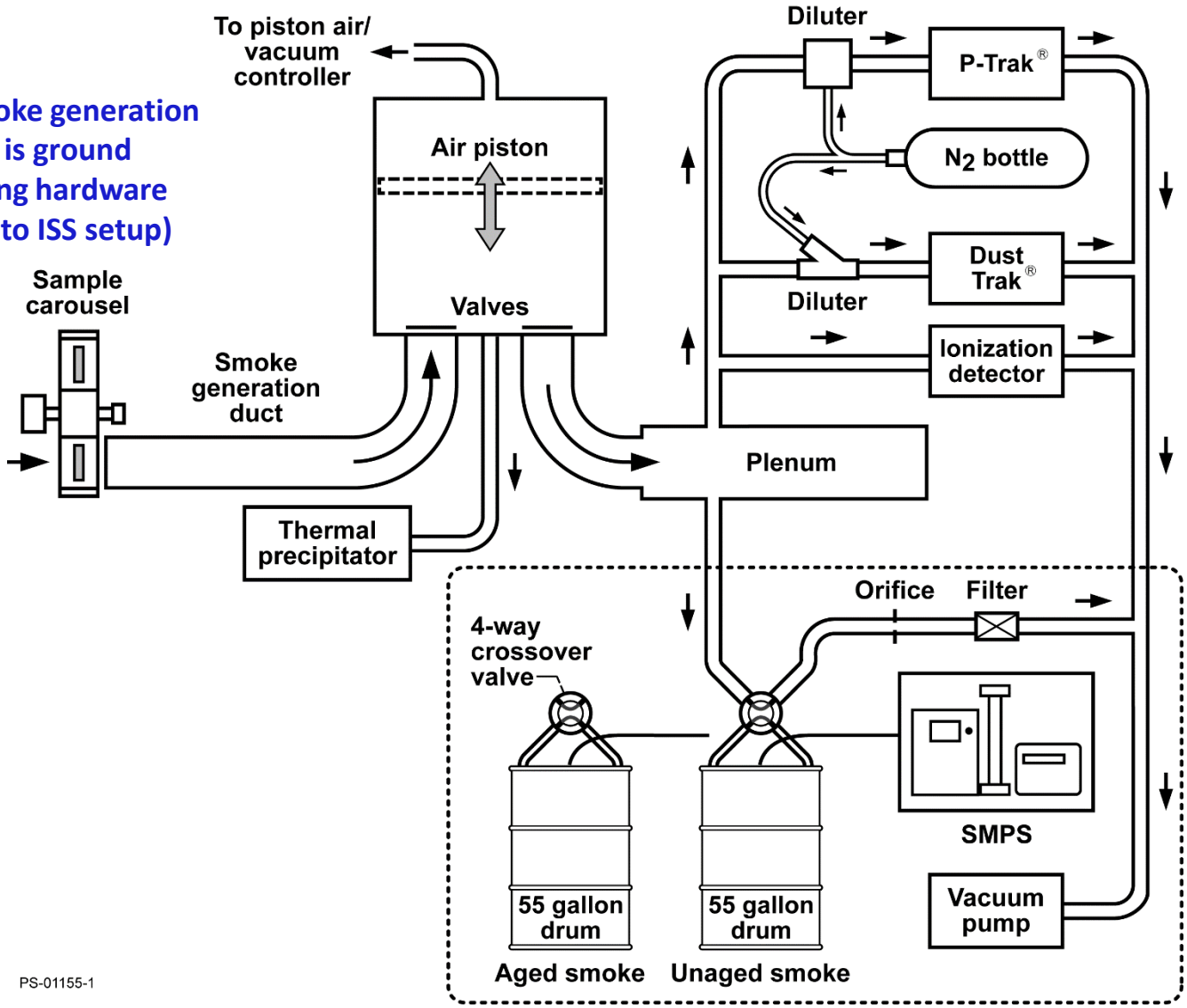
scale bars = 2 µm

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)

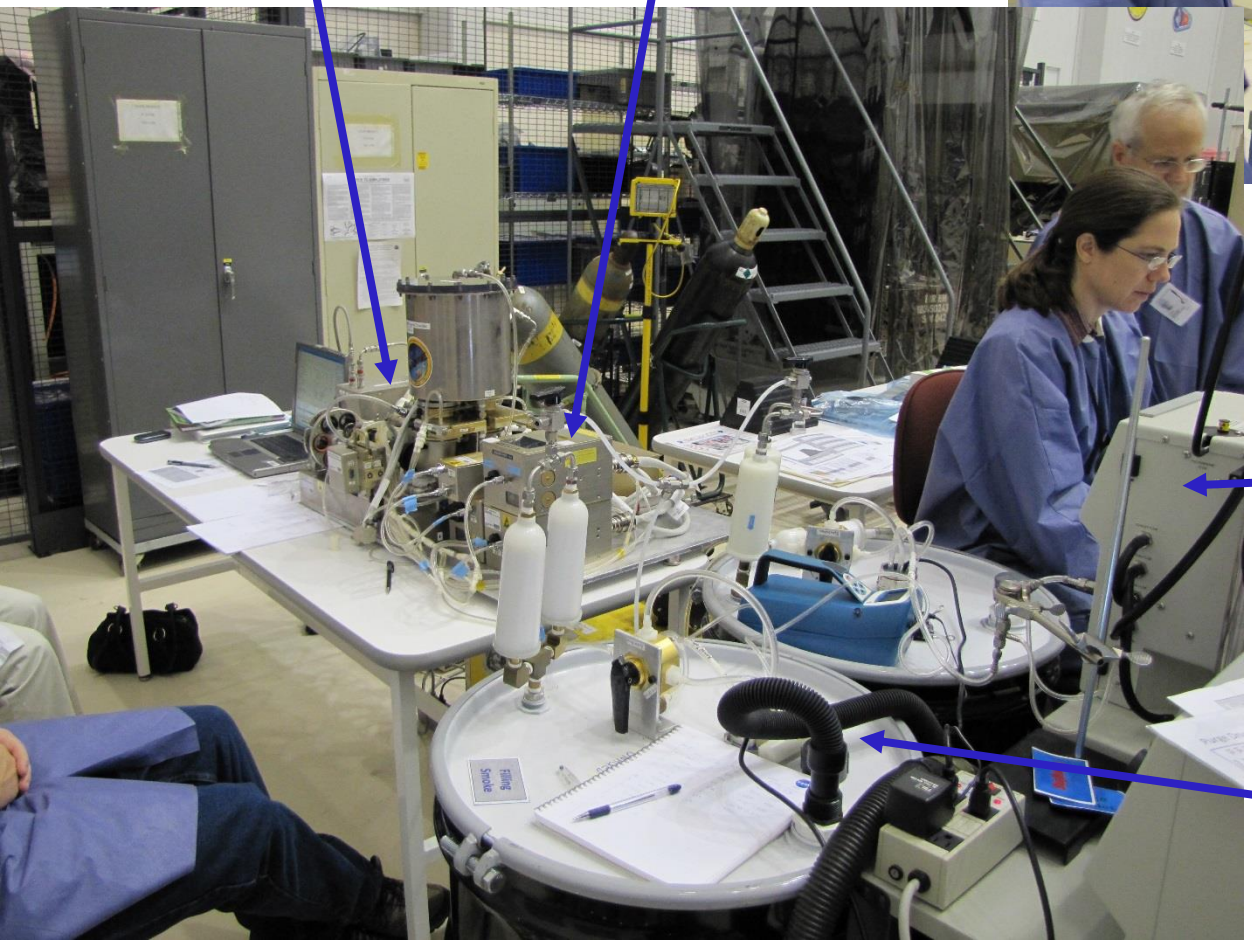


Instruments are units returned from ISS

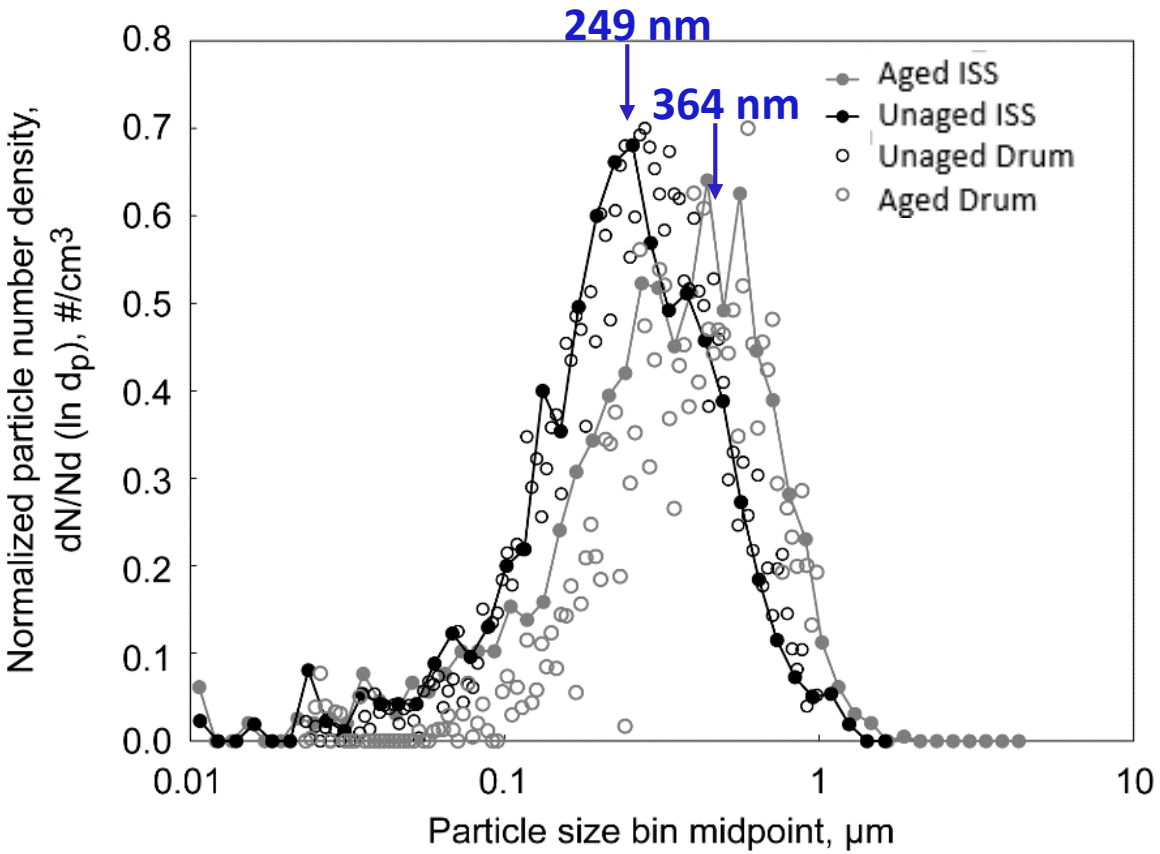
Smoke-in-Drums Experiment

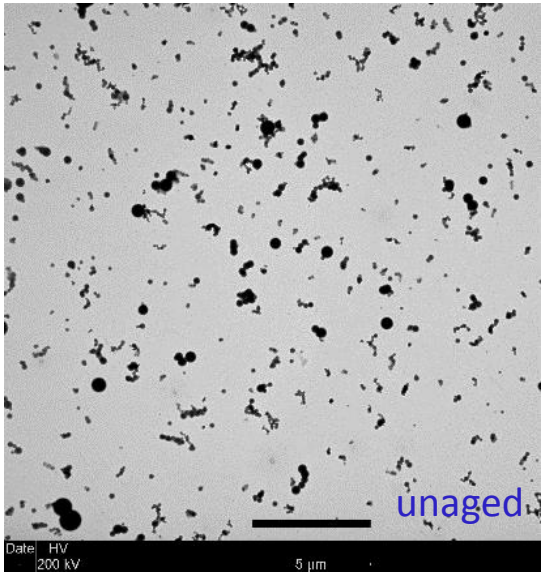
SAME
engineering HW
makes smoke

Small instruments
returned from ISS



Compare Particle Size Distribution: Pyrell

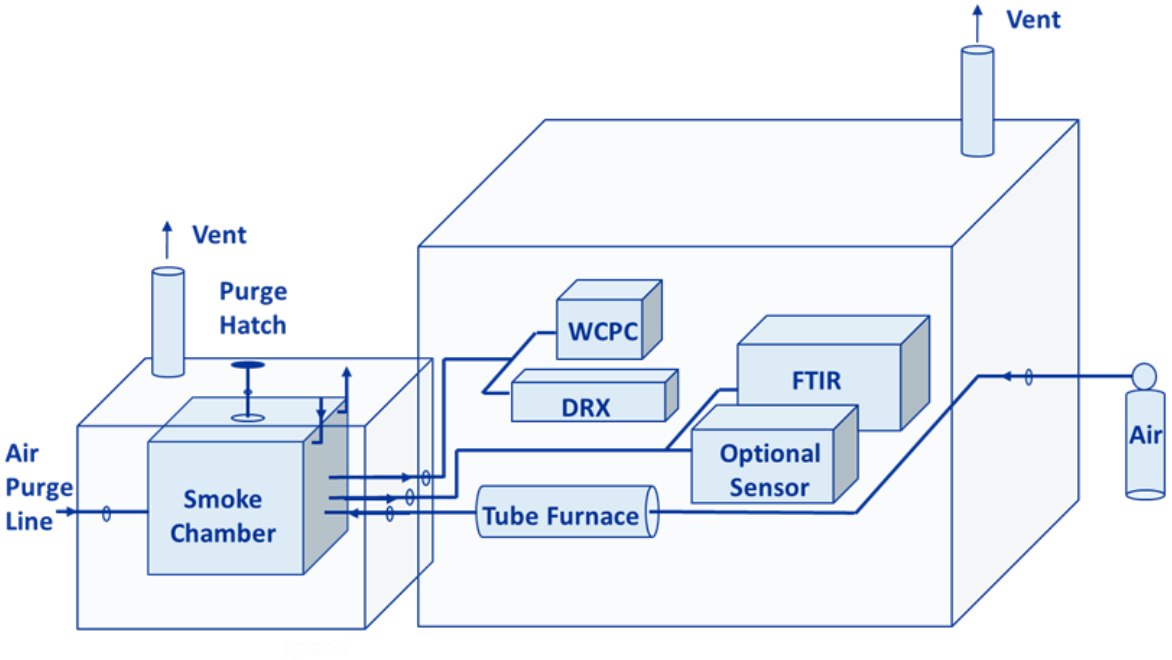




- ISS flight, 242 °C
- Smoke-in-drums, 234 °C

Meyer et al. 2015, 'Smoke Characterization and Feasibility of the Moment Method for Spacecraft Fire Detection,' DOI: 10.1080/02786826.2015.1025124

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

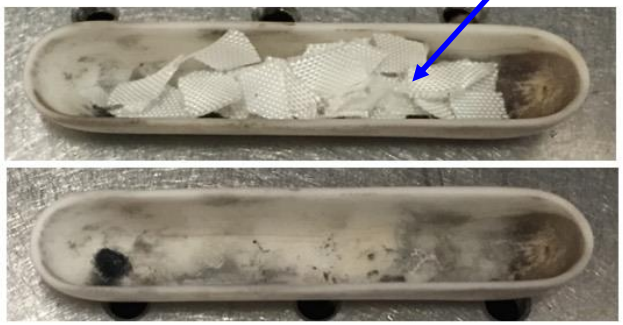
COTS=Commercial-off-the-shelf

GASP Fuels

Nomex, a heat and flame-resistant woven textile, used for acoustic insulation, cargo bags, thermal blankets & pressure suits

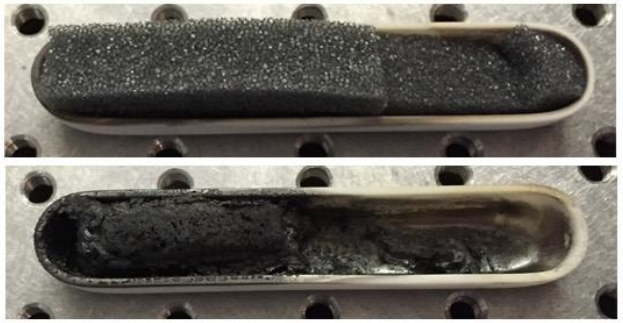
Lamp wick

Nomex



Kapton and wire
(M22759 and PVC-insulated)

Pyrell



GASP Fuels

Tobacco

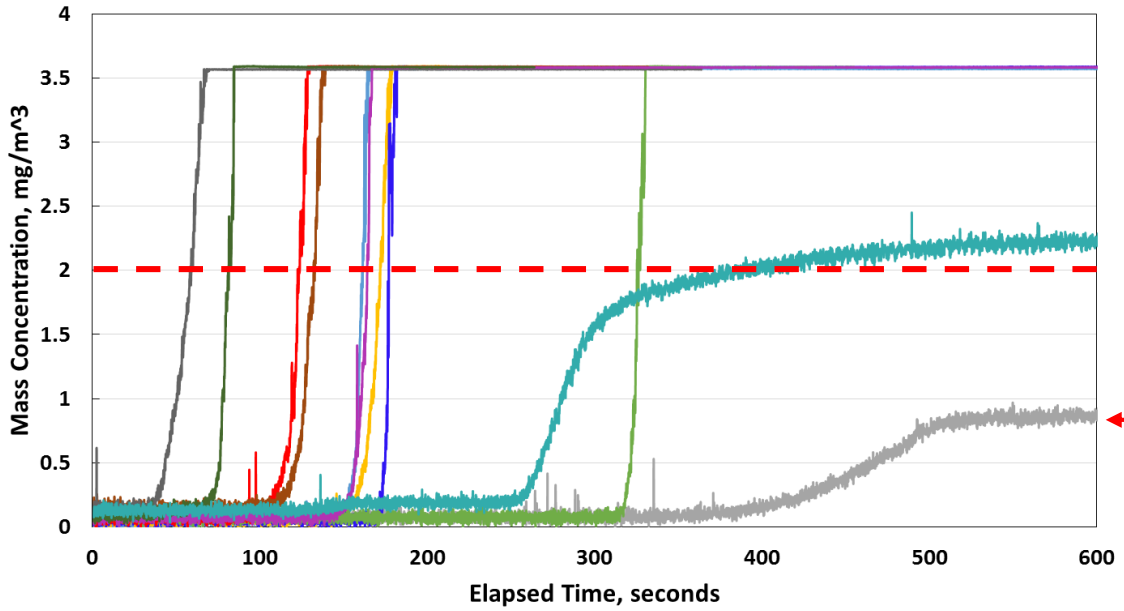
Teflon piece

Components

Bulk Kapton

Components: several thin film resistors, a tantalum capacitor, an inductor and a resin-encapsulated LED with the leads removed

GASP Experiments: Early Fire Detection



ISS smoke detector alarm threshold = 2 mg/m^3

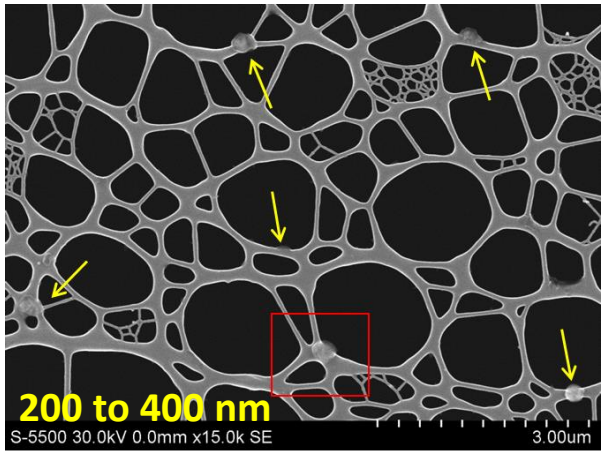
Teflon smoke generated would never trigger alarm

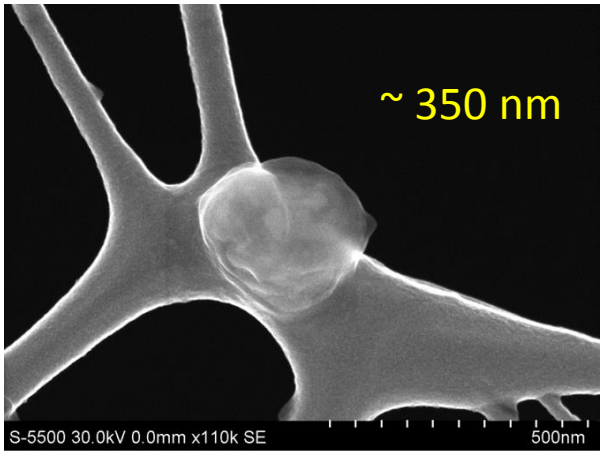
- Kapton snips
- Bare PCB pieces
- Tobacco
- Pyrell
- Chunk Teflon
- Components
- Nomex snips
- Bulk Kapton
- PVC wire
- Lamp wick
- Wire & bulk Kapton, humidified

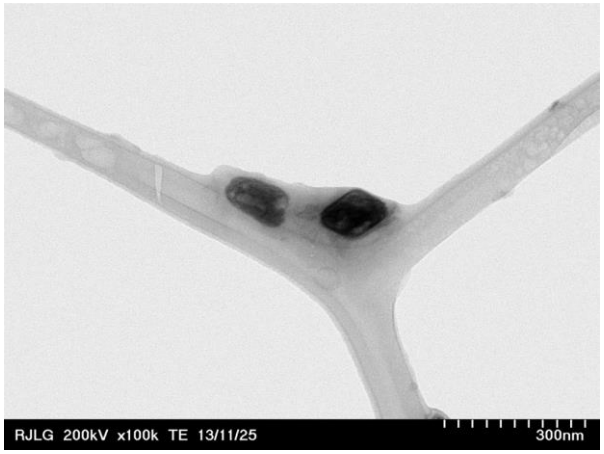
Detection times from 1 minute to 6 minutes (Teflon is infinity)
Too slow!

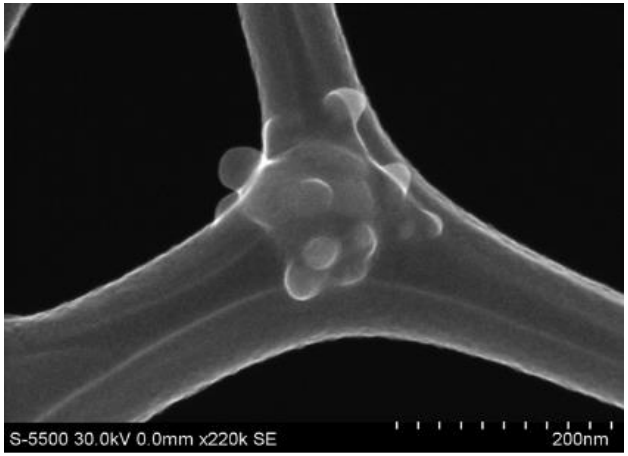
PCB is 'printed circuit board' (bare FR-4)

Circuit board & Components



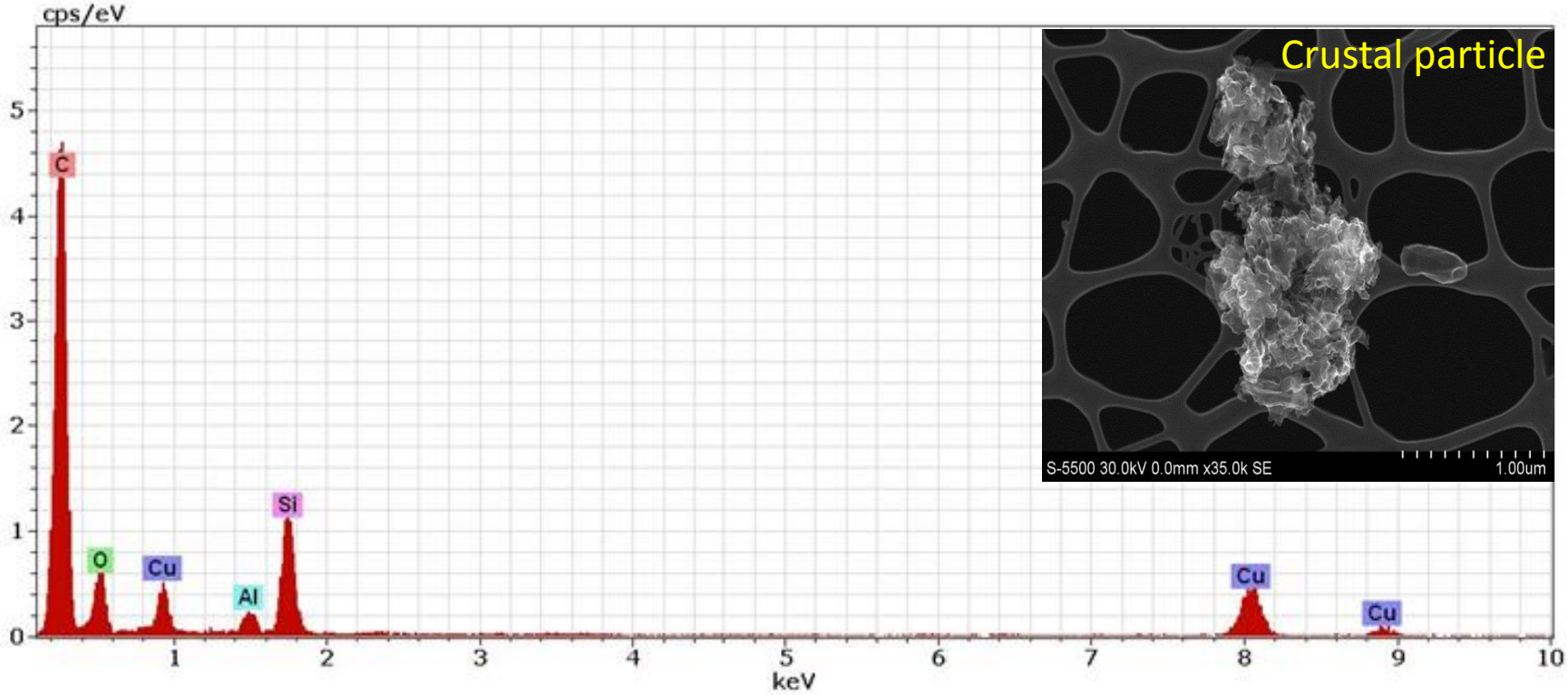






Images and microscopy data courtesy of RJ Lee Group

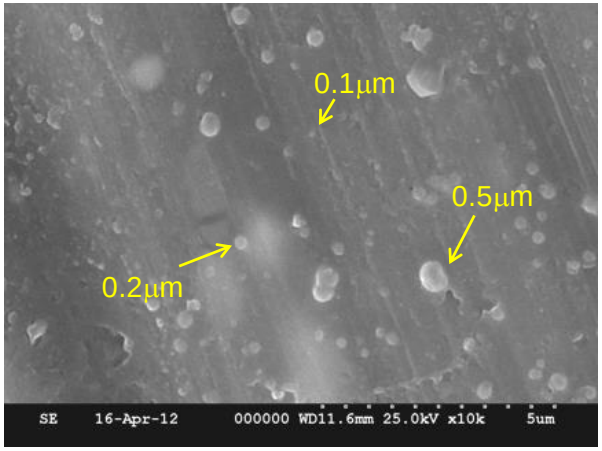
Circuit board & Components

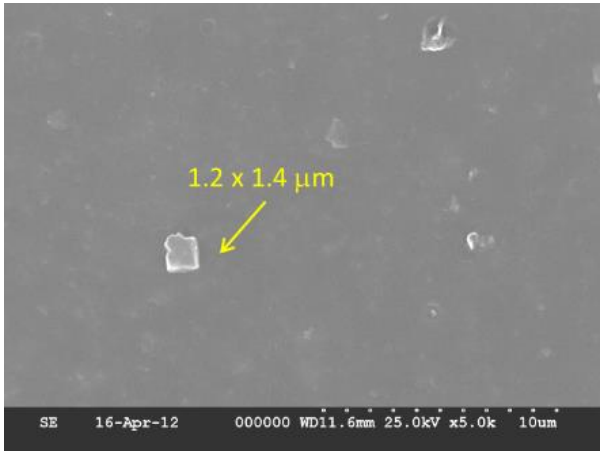


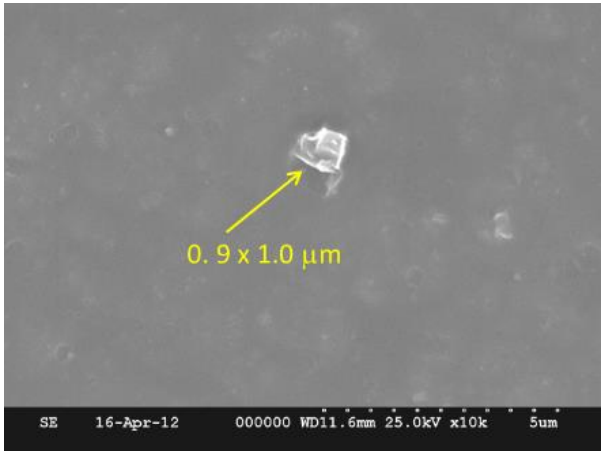
Microscopy courtesy of RJ Lee Group

Wire Insulation Smoke Particles

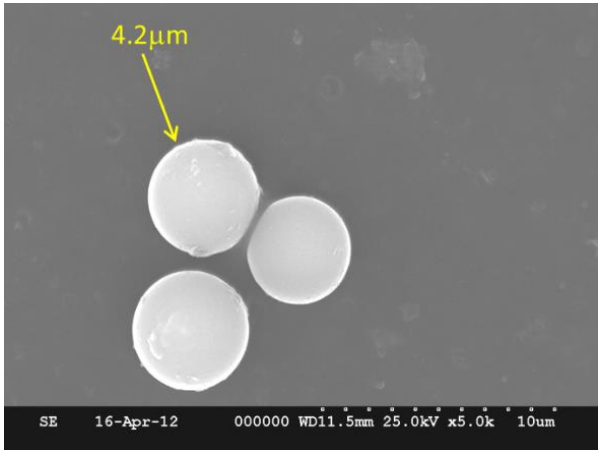
(partially fluorinated polyimide, PFPI)

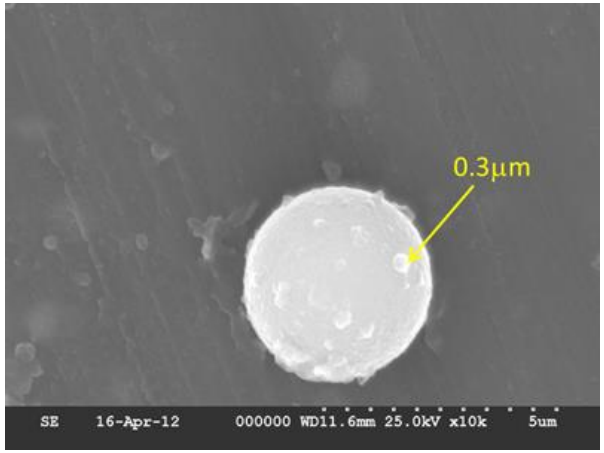






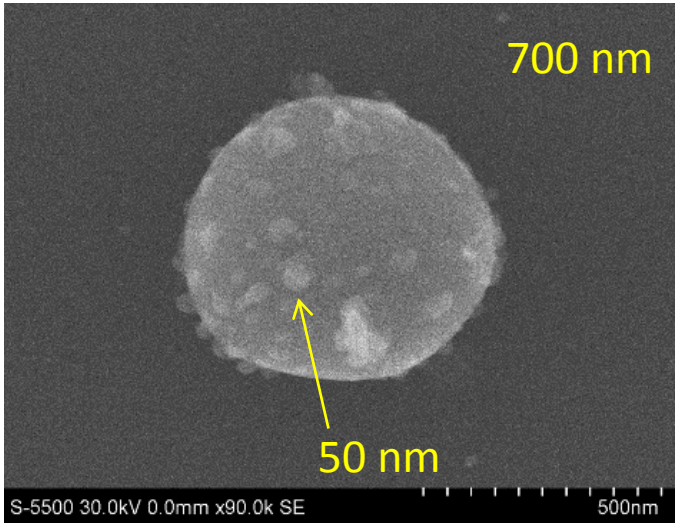
Crystalline particles

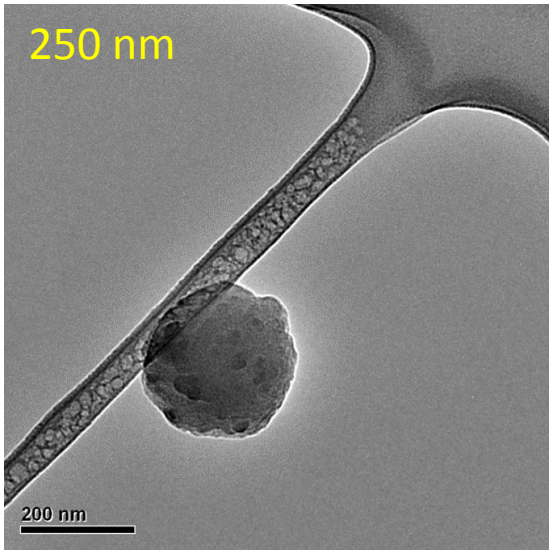


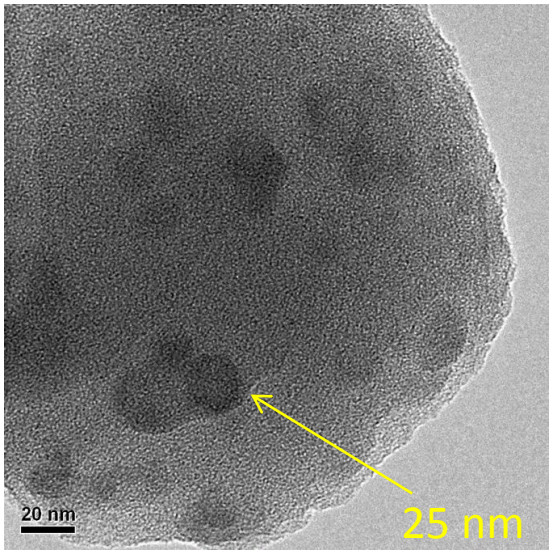


Images courtesy of RJ Victoria Bryg/NSCER

Teflon Smoke Particles

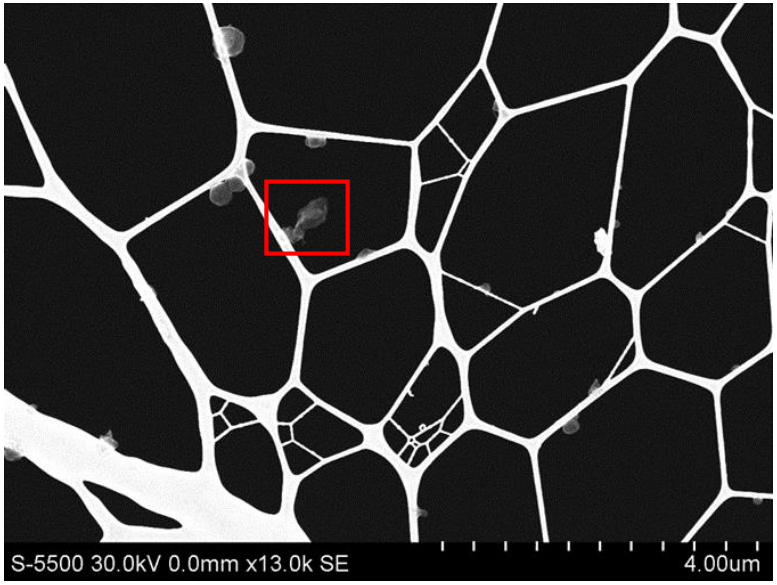


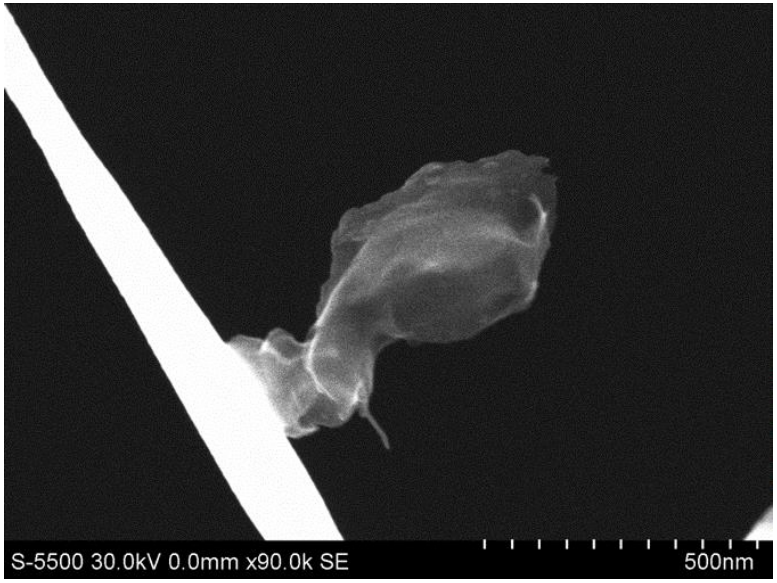


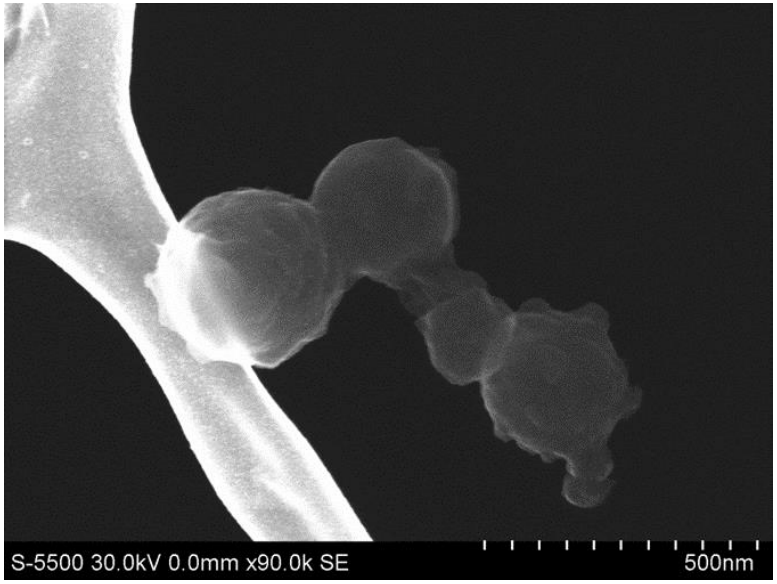


Images courtesy of RJ Lee Group and Victoria Bryg/NSCER

Kapton Smoke Particles



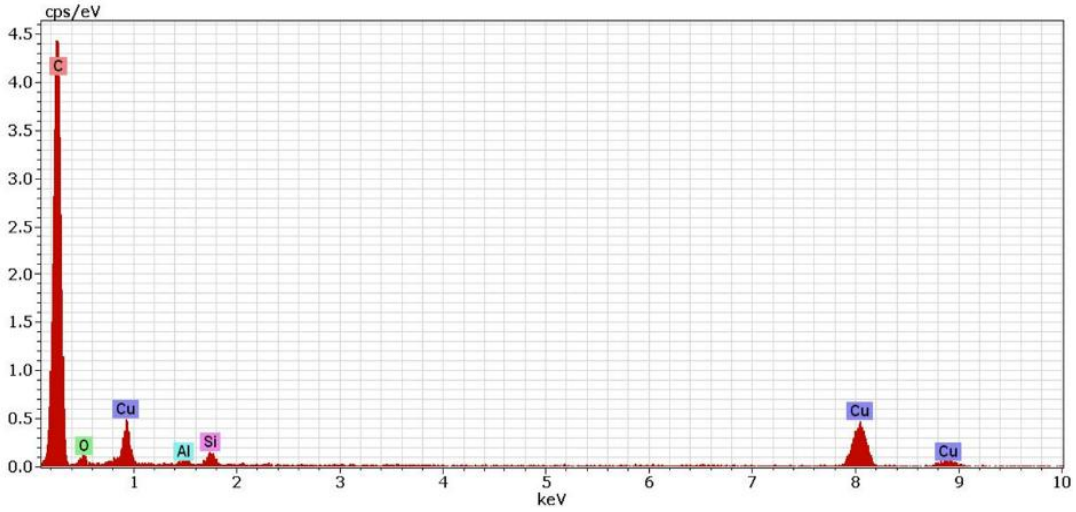


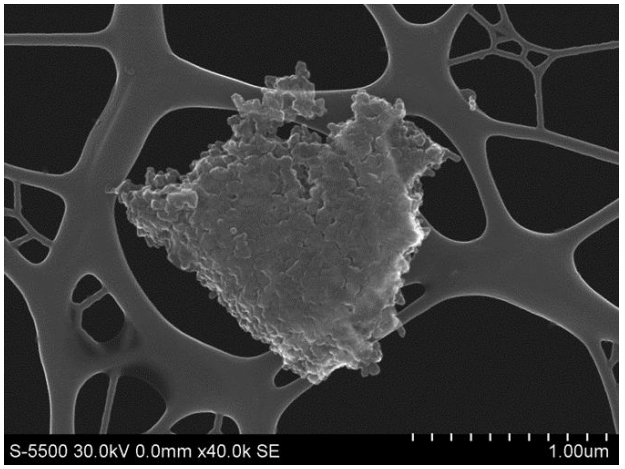


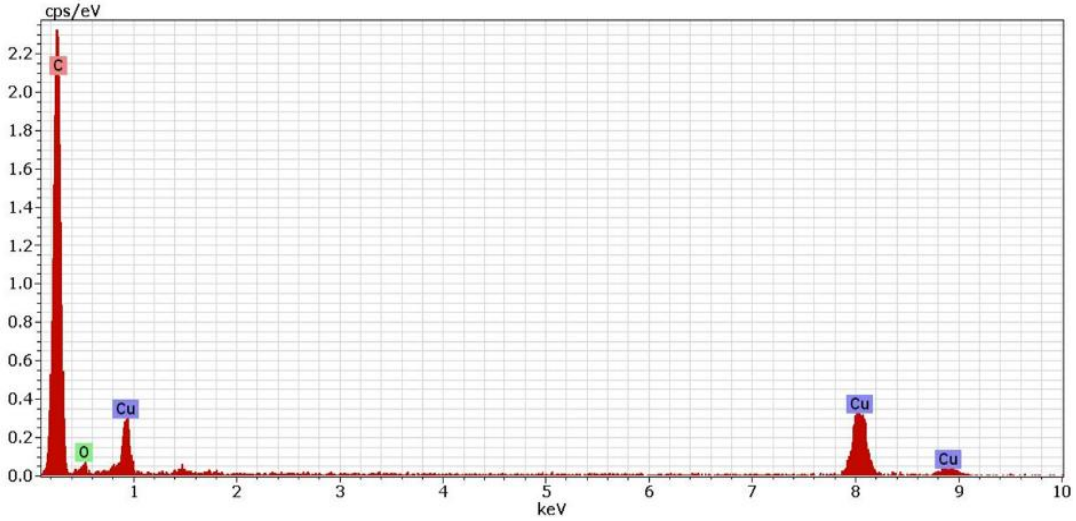
- Thermal decomposition of Kapton results in liquid aromatic products
- The general spherical shape of the particles observed is consistent with the particles starting as a liquid solution with many components
- Chain-like agglomerates, 100 to 350 nm primaries

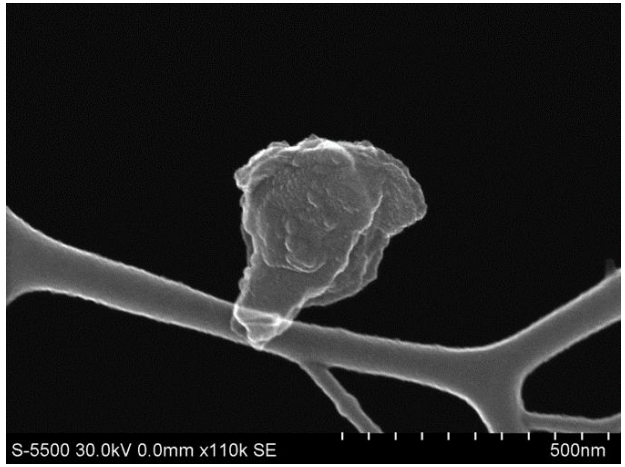
Images courtesy of RJ Lee Group and Victoria Bryg/NCSER

Nomex Char Particles



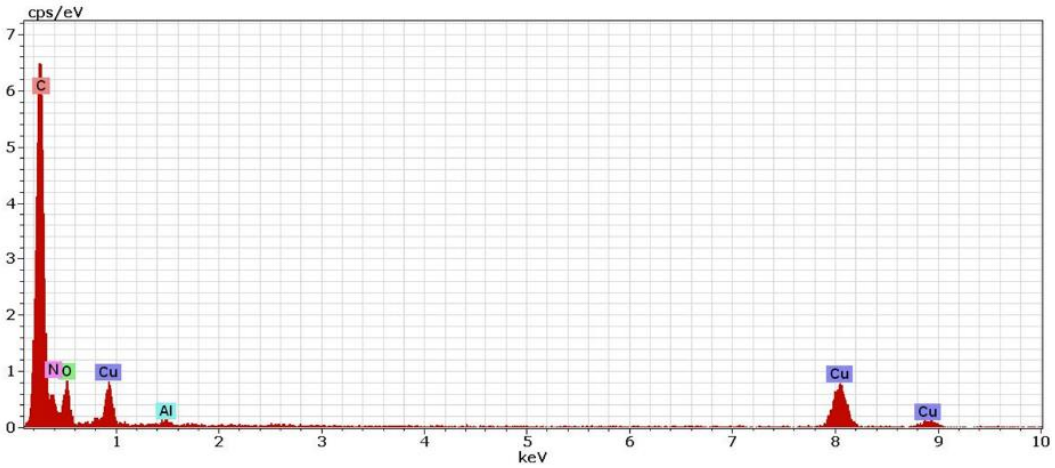


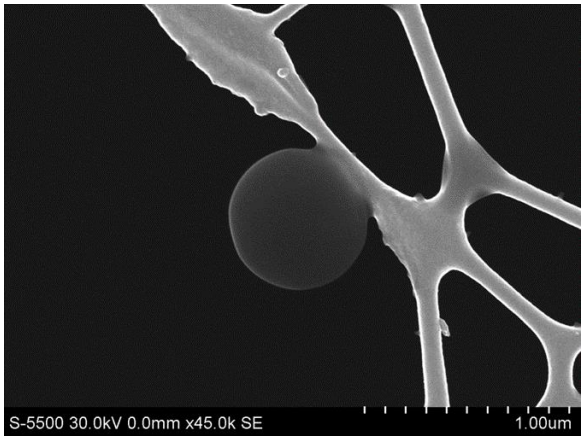


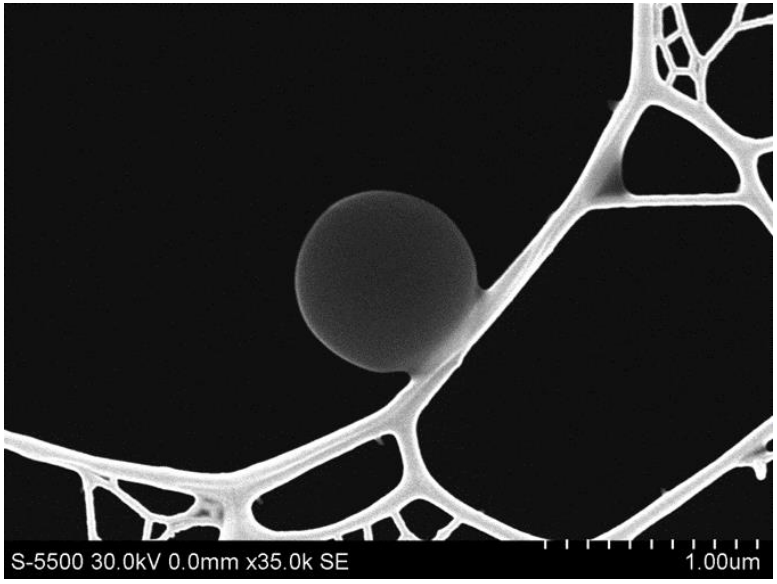


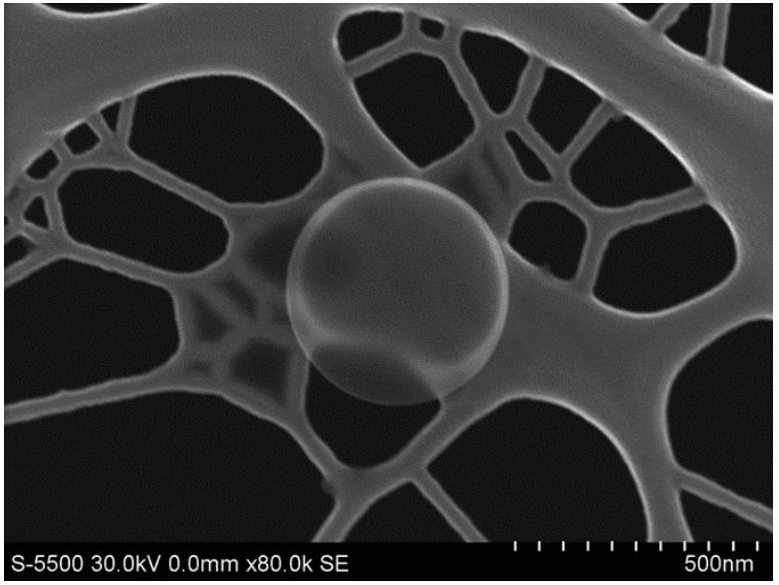
Microscopy courtesy of RJ Lee Group

Nomex Tar Balls









Images courtesy of RJ Lee Group

We need a ‘big burn’!

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

FAA full scale aircraft test

Naval Research Laboratory Ex-USS Shadwell

Controlled burns of structures

Most U.S. agencies responsible for large transportation systems conduct full-scale fire tests

SAFFIRE: Spacecraft Fire Safety Demonstration

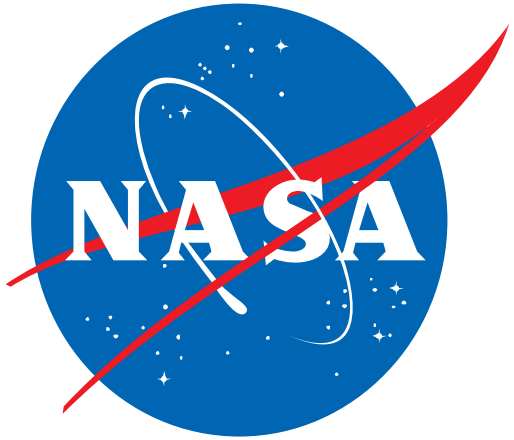
- Use a disposable cargo vehicle for a fire experiment just before de-orbit and destruction
- SAFFIRE I, II, III
  - Orbital Cygnus vehicle
- SAFFIRE IV, V, VI
  - SpaceX Dragon vehicle

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

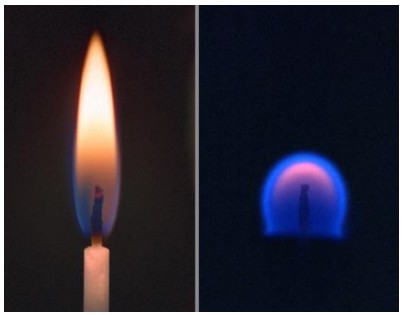
- Study combustion in a range of ambient environments
- Study liquid, gaseous and solid fuel combustion
- Modular and upgradeable to improve capabilities as technologies mature
- Capable of remote, nearly autonomous operation

The ISS Experiment manifest

- Droplet Combustion – FLEX (2009 – 2016)
- Gaseous Combustion – ACME (2017 – 2018)
- 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://www.theverge.com/2016/3/16/11244364/nasa-saffire-test-fire-orbital-atk-cygnus-iss-resupply-mission (links to Saffire animation)
- http://phys.org/news/2016-03-nasa-space-unmanned-orbiting-craft.html
- http://m.voanews.com/a/nasa-plans-to-light-large-fire-in-space/3240548.html
- http://www.sciencealert.com/nasa-is-going-to-start-a-large-fire-in-space-in-the-name-of-science (Has a video of FLEX.)
- 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)
- http://en.people.cn/n3/2016/0317/c90000-9031350.html
- https://www.rt.com/usa/335874-nasa-fire-space-cygnus/ (Another link to Saffire video)
- http://www.independent.co.uk/news/science/nasa-to-set-a-ship-on-fire-in-space-to-test-safety-in-emergencies-a6934081.html (Shows the ISS)
- https://www.yahoo.com/news/nasa-test-fire-space-burning-unmanned-orbiting-craft-081545440.html
- http://spaceflightnow.com/2016/03/16/scientists-to-start-fire-in-discarded-spacecraft-for-weightless-flames-study/

Smoke Characterization and Feasibility of the Moment Method for Spacecraft Fire Detection

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The Smoke Aerosol Measurement Experiment (SAME) has been conducted twice by the National Aeronautics and Space Administration and provided real-time aerosol data in a spacecraft micro-gravity environment. Flight experiment results have been recently analyzed with respect to comparable ground-based experiments. The ground tests included an electrical mobility analyzer as a reference instrument for measuring particle size distributions of the smoke produced from overheating five common spacecraft materials. Repeatable sample surface temperatures were obtained with the SAME ground-based hardware, and measurements were taken with the aerosol instruments returned from the International Space Station

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

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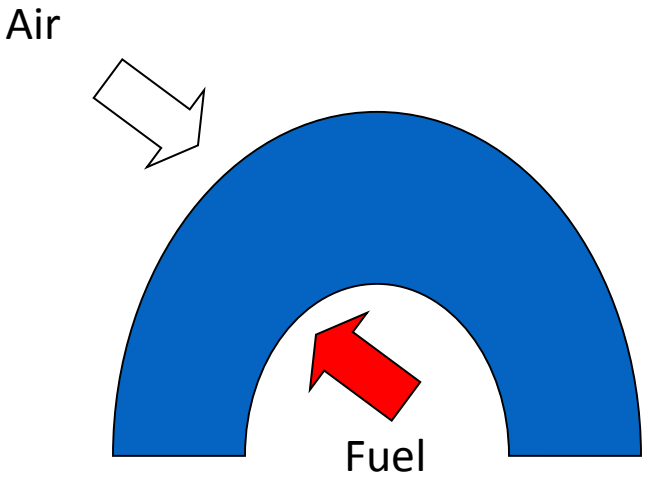


Basics

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

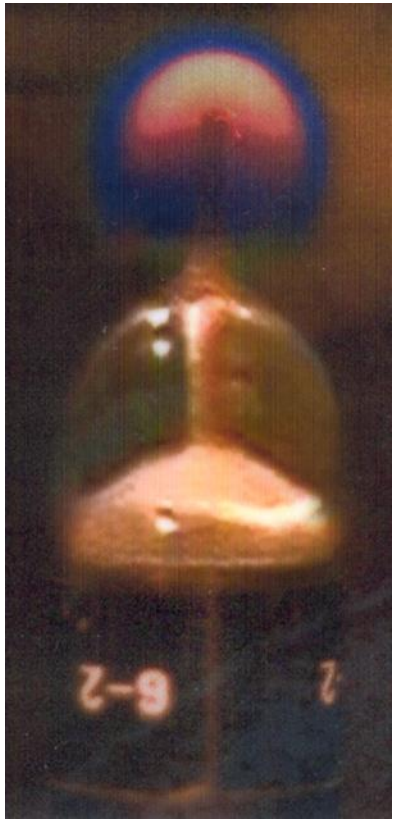
Heat Loss Rate

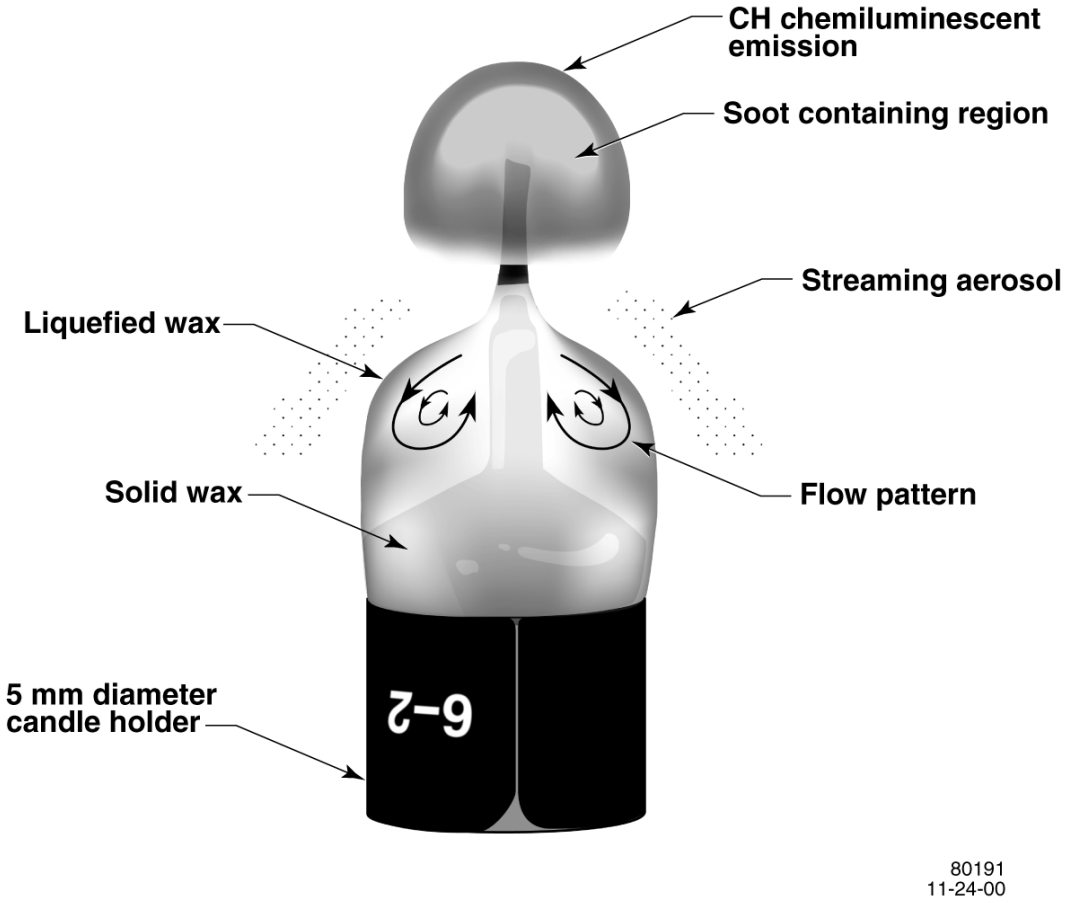
- Radiation, Conduction, Convection – all functions of temperature difference between fire and surroundings

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…