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Measurement of Smoke Particle Size under Low-Gravity Conditions

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ABSTRACT

Smoke detection experiments were conducted in the Microgravity Science Glovebox (MSG) on the International Space Station (ISS) during Expedition 15 in an experiment entitled Smoke Aerosol Measurement Experiment (SAME). The preliminary results from these experiments are presented. In order to simulate detection of a prefire overheated-material event, samples of five different materials were heated to temperatures below the ignition point. The smoke generation conditions were controlled to provide repeatable sample surface temperatures and air flow conditions. The smoke properties were measured using particulate aerosol diagnostics that measure different moments of the size distribution. These statistics were combined to determine the count mean diameter which can be used to describe the overall smoke distribution.

INTRODUCTION

Current spacecraft fire detection systems have all been designed based on normal gravity fire behavior and properties. This approach was necessary given the absence of data concerning microgravity smoke particulate. However planned spacecraft and associated missions outside of low earth-orbit will require increased reliability of fire detection systems in addition to robust false alarm resistance. Extended lunar-surface missions will require systems that are not influenced by lunar dust and other nuisance dust sources. The absence of buoyant flow increases the residence time in microgravity fires causing substantial changes in flame structure and consequently can change the properties of the produced smoke. In particular, the increased residence time in the high temperature zone where the smoke is formed, can increase the opportunity for growth in the size of the smoke particulate. Furthermore, the increased transit time to the detector seen in low-gravity smoke detection scenarios [1] provides additional time for growth in particle size through aging or low temperature agglomeration of smoke particles. The objective of this work is to make sufficient measurements of smoke from spacecraft fires to enable improved design of future detectors.

SMOKE BACKGROUND

The background in fire detection in US spacecraft is discussed by Urban et al. [2] however some details will be summarized here. Smoke is a general term that encompasses aerosol materials produced by a number of processes. In particular it can include unburned, recondensed, original polymer or pyrolysis products that can be either liquid or solid, hydrocarbon soot, condensed water vapor, and ash particles. Ash and soot particles dominate the smoke particulate in established 1-g flaming fires while unburned pyrolysis products and recondensed polymer fragments are produced by smoldering and pyrolysis in the early stage of fire growth. Given the constrained space on any spacecraft, the target for the fire detection system is necessarily the early phase and not established flaming fires; consequently, the primary target for detection is the pyrolysis products and not the soot and ash.

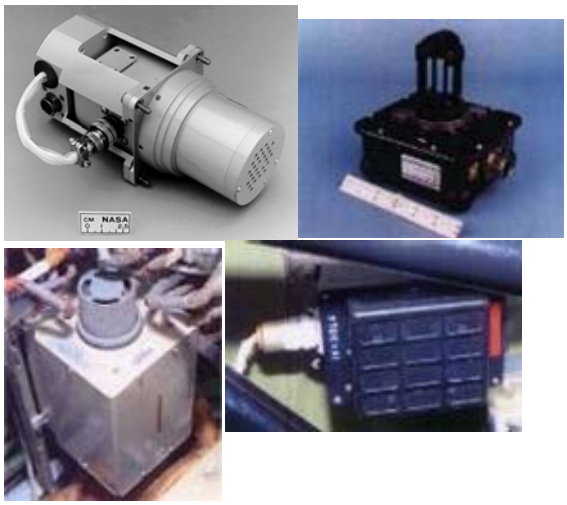

Figure 1: Current Spacecraft smoke detectors. *Clockwise from top left: ionization smoke detector used in the NASA Orbiter fleet; light scattering detector used in the US lab on the ISS; ionization detector used in the Russian ISS Service Module; and ionization detector used in the Russian ISS FGB Module.*

In the Mercury, Gemini and Apollo missions, the crew quarters were limited and mission durations were short, consequently it was considered reasonable that the astronauts would rapidly detect any fire. The Skylab module, however, included approximately 30 UV-sensing fire detectors [3]. The US Space Shuttle and the Russian segments of the ISS all use ionization smoke detectors while the US, JEM and Columbus labs of the ISS use light scattering detectors. The systems currently in use are shown in Figure 1.

Light scattering devices are most sensitive to particulate whose size is of the same order as the wavelength of the light used by the detector, typically particle diameters greater than 0.3 μm. Ionization devices are more sensitive to smaller particles. As reviewed by Urban et al. [2] this difference in size sensitivity is significant for some types of fires, consequently ionization and scattering detectors have different performance for normal-gravity fires. Proper implementation of smoke detection requires understanding of the smoke particle size distribution. Low-gravity smoke particle size data were not available when the existing systems were designed, consequently the designers used 1-g smoke detector designs. These design decisions led to detectors on the ISS and the Space Shuttle Orbiter that, in general, have non-overlapping particle size sensitivities.

As described by Friedman [4] there have been six overheated electrical component events in the NASA Orbiter fleet. None of these events spread into a real fire but as mission durations increase, the likelihood of failures increases. The experience on Mir in 1997 has shown that failure of oxygen generation systems can have significant consequences. As a result, improved understanding of spacecraft fire detection is critically needed. [5]

Urban et al. [2] reported that particulate produced by low-gravity flames (soot or unburned fuel particles) tends to have larger size particles than in normal gravity. Results from the CSD (Comparative Soot Diagnostics) Experiment [2] which studied smoke properties in low-gravity from several spacecraft materials suggested that liquid smoke particles could achieve sizes larger than 1 μm while solid particulate remained in the sub-micrometer range. The combined impact of these limited results and theoretical predictions is that direct knowledge of low-g combustion particulate rather than extrapolation from 1-g data is needed for more confident design of smoke detectors for spacecraft.

Any effort to detect fires must be able to discriminate against the ambient background and nuisance signals. In the case of smoke detection, the background dust aerosol conditions must be considered. The only spacecraft background aerosol particulate measurements to date were made on the Orbiter on STS-32 in 1990 [6] and on the ISS. [2] The STS measurements reported a bimodal particle size distribution with ~ 40% of the particles in each of the 2.5 to 10 μm and >100 μm ranges. The other two ranges <2.5 μm and 10 to 100 μm were very lightly populated. These results showed substantially higher concentrations than typical indoor measurements (over a factor of 5 for the two most populated size ranges). The ISS results of Urban et al. [2] were a secondary result of an experiment to validate the operation of an aerosol particle counter in low-gravity. The measurements were made in the US Lab on Increment 10 and the particle count levels were at the noise level for the instrument (less than 5 particles/cc). The low particle levels in the < 2.5 μm bin for the STS and the low overall numbers for the ISS suggest a zone of opportunity for spacecraft fire detection since typical normal gravity fires produce substantial particulate in this size range[2,7]. However more complete particle size statistics are needed.

SAME EXPERIMENT CONCEPT

To date the only data on low-gravity smoke particulate were collected by the CSD experiment[2]. The CSD data set was not particularly large as the size statistics were obtained from TEM data, critical details were not obtained for the liquid droplet aerosols and the smoke flow conditions were not well characterized. To rectify these concerns, another experiment, the Smoke Aerosol Measurement Experiment (SAME) was developed. The SAME experiment sought to avoid the problems experienced by the CSD experiment by obtaining the particulate size statistics on-orbit with a reduced dependence upon sample return to Earth. This is a challenging endeavor because existing aerosol instrumentation is typically large, incompatible with spacecraft experiment constraints, and may require substantial sample return to Earth. As will be described below, an alternative approach was employed that used three discrete instruments to measure separate moments of the size distribution. When combined, these

moments provide useful aggregate statistics of the size distribution. The measurements were made using smoke generated by overheated spacecraft materials in much the same manner as the CSD experiment however the sample temperature, flow field, and particle aging time were more rigorously controlled.

MOMENT METHOD

The approach used by the SAME experiment is termed the 'moment method' for convenience[8]. As will be described below, the approach consists of measuring three moments of the size distribution (zeroth, first and third) and using the properties of the log-normal distribution to estimate the geometric mean diameter and the standard deviation.

The average particle size and an estimate of the width of the size distribution will be estimated from various moments of the size distribution. Consider a number distribution, $f_N(D)$, that is defined as

$$f_N(D) = \frac{dN}{dD} \quad (1)$$

where dN is the number of particles per cm^3 with diameter between D and D + dD. The moments of interest consist of the number concentration, M_0, the first moment M_1, and the volume or mass concentration moment, M_3 As defined in Eq. 2.

$$M_i = \int D^i f_N(D) dD \quad i = 0,1,3 \quad (2)$$

The first moment which can also be thought of as the "diameter concentration" or integrated diameter-per-unit-volume is approximately proportional to the signal from an ionization smoke particulate detector. For particles in the Mie scattering regime, particles sizes from 0.3 λ to about 3 λ (~0.2 to 2.0 μm for a red laser) the light scattering signal is approximately proportional to the third moment. From these moments, and a measurement of M_0 from a condensation nuclei counter, two mean diameters can be computed: the count (arithmetic) mean diameter $D_{0.5}$ or $\overline{d}$, which is equal to M_1/M_0 and the diameter of average mass $D_{1.5}$ or $d_{\overline{m}}$, which is equal to $(M_3/M_0)^{1/3}$. The log-normal size distribution is widely used for describing the size distribution of aerosols including non-flaming smoke. For smokes, as in most aerosols, the bulk of the number concentration is associated with smaller particles.[9, 10] The form of this distribution function is the same as the normal distribution except that the diameter is replaced with the ln D so that one has

$$f_N(D) = \frac{N_t}{(2\pi)^{1/2} D \ln \sigma_g} \exp\left(-\frac{(\ln D - \ln D_g)^2}{2 \ln^2 \sigma_g} \right) \quad (3)$$

where N_t is the total number concentration of the aerosol (=M_0), and D_g and σ_g are the geometric mean number diameter and geometric standard deviation defined by

$$\ln D_g = \int_0^\infty \ln D f_N(D) dD \Big/ \int_0^\infty f_N dD \quad (4)$$

$$\ln \sigma_g = \left[\int_0^\infty (\ln D - \ln D_g)^2 f_N(D) dD \Big/ \int_0^\infty f_N(D) dD \right]^{1/2} \quad (5)$$

For the log-normal distribution, one finds that the various diameter definitions are related to the geometric mean number diameter, D_g, via the equation: [9, 10]

$$D_p = D_g \exp(p \ln^2 \sigma_g) \quad (6)$$

For the count mean diameter, $D_{0.5}$, and the diameter of average mass, $D_{1.5}$, the corresponding values of p are 0.5 and 1.5. As an example, for a log-normal distribution with D_g=1.0 μm and σ_g=2.0, the corresponding values of $D_{0.5}$ and $D_{1.5}$ are 1.27 μm and 2.06 μm, respectively. Using equation (6), one can relate σ_g to the ratio of $D_{1.5}$ and $D_{0.5}$ via the equation:

$$\sigma_g = \exp\left(\ln(D_{1.5} / D_{0.5})\right)^{1/2} \quad (7)$$

In summary, by combining these three measured moments of the size distribution, M_0, M_1, and M_3, it is possible to compute three mean diameters of the size distribution, $D_{0.5}$, $D_{1.5}$, and D_g, and the geometric standard deviation, σ_g. Validation of this approach is discussed in Cleary, Weinert and Mulholland. [8] These statistics provide a strong basis for design of spacecraft smoke detectors.

SAME EXPERIMENT DESIGN

The experiment was developed as a Microgravity Science Glovebox (MSG) payload under the ISS research program. A schematic of the experiment hardware appears in Fig. 2 and an assembled photograph in Fig. 3. Smoke was generated by overheating a small sample of material in the smoke generation duct for approximately 60 seconds. During this interval, controlled flow over the sample was

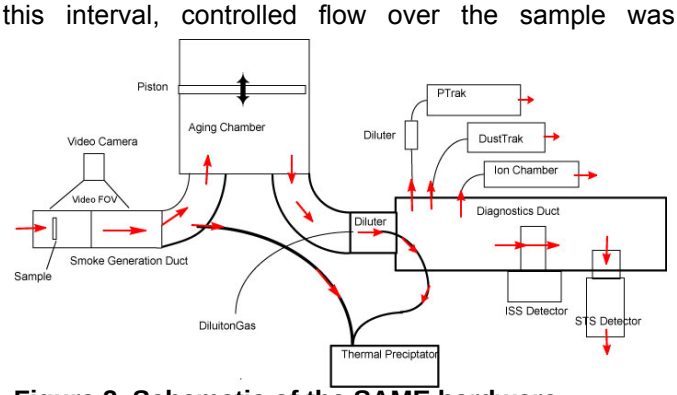

Figure 2. Schematic of the SAME hardware.

Figure 3: Engineering model of the SAME hardware installed in a MSG simulator. *The sample carousel is on the left side, the large vertical cylinder is the aging chamber and the moment instruments are on the right side. (Clockwise from top left): Dynamic Diluter for the zeroth moment instrument, Commercial Diagnostics Unit A (first and third moments), Commercial Diagnostics Unit B, Zeroth Moment instrument. The ISS and STS smoke detectors are visible to the left of the aging chamber.*

induced by a moving piston in the aging chamber which drew the smoke into the chamber. The smoke was held in the chamber for a predetermined time, allowing the particles to coagulate. The smoke was then pushed by the piston into the diagnostics duct where the moment instruments made their measurements. Also installed in the diagnostics duct were Space Shuttle and ISS smoke detectors. As the smoke was monitored by the moment instruments, a sample of the smoke particles was deposited on Transmission Electron Microscope (TEM) grid via a thermal precipitator which uses thermophoresis to deposit the particles on the grids.

Smoke was generated by resistively heating small samples of spacecraft materials. Sample heating was achieved by heating a steel wire that was wrapped around an approximately 3mm diameter cylinder of the sample material. The steel wire was resistively heated and the wire resistance was monitored to control its temperature. This technique was found to produce repeatable weight loss from sample to sample. Groups of six preweighed samples were installed in carousels (Fig. 4) that the crew installed in the SAME hardware. For each test, a new sample was moved into place and the sample heating and the flow were synchronized to provide a steady air stream over the sample during the heating interval. The system was designed to provide air flow rates ranging from 2 to 8 cm/s. To emulate a variety of fire scenarios, tests were conducted at different sample temperatures, air flow rates, and smoke aging durations. Five material were tested, Teflon™, Kapton™, silicone rubber, lamp wick (cellulose) and a reference material (dibutyl phthalate).

Figure 4. Photograph of a sample carousel. *Carousel contains an assortment of Teflon, Kapton, lamp wick, and silicone rubber. The samples were supported and heated by the same stainless steel wire coil.*

INSTRUMENTS

The moment measurements were made using an assembly of three separate instruments. Two are industrial hygiene instruments manufactured by TSI Inc. and one is a modified residential smoke detector. The zeroth-moment instrument is a condensation nuclei counter P-Trak™ (TSI Inc.). This device operates by passing the aerosol-laden particle stream through a volume saturated with isopropanol vapor and then into a cooler region where the vapor condenses onto the particles raising them all to a size where they are readily counted by a light scattering device. This instrument is very robust and operates over a range of 0 to 10^5 particles/cm^3 and 20 nm to 5 μm diameter. Some dilution is required since the smoke concentration ranges from about 0.5×10^6 to 5×10^6. There was also a concern that the isopropanol condensate would not return to the wick in low-gravity. [2] To mitigate this issue, the condensing section of the device was modified with very small grooves to improve conductance of the condensate back to the wick. These changes were tested in a separate space experiment with good results indicating the modified device could be used successfully in low gravity [2]. The device was repackaged into an enclosure (Fig. 3) and the internal air pump was replaced with a choked-flow orifice that vented into the MSG vacuum resource.

The first and third moment instruments were packaged together in a single enclosure and two of these combined enclosures were used simultaneously during SAME operations. The first-moment instrument is the ionization chamber from a residential smoke detector which uses an alpha-particle emitter to generate ions in a region inside a DC electric field. The sensor measures the voltage of a reference electrode inside this field. The presence of particulate changes the charge distribution (and thereby the reference electrode voltage) as a result of the attachment of the ions to the particulate. The

required particle concentrations are on the order of 10^5 particles / cm^3 and no sample dilution was required. The sensor was enclosed in a chamber through which the smoke was drawn at a controlled velocity by the MSG vacuum resource.

The third-moment instrument is a light scattering device DustTrak™ (TSI Inc.). The device uses a 90 degree light scattering signal to quantify the aerosol mass density. For terrestrial dust particulate this signal correlates well with the mass concentration, however additional compensation will be needed to account for the range of particle sizes that will be seen in the SAME experiment. The device operating range is from 0.001 to 100 mg /m^3. These devices are equipped with an aerodynamic impactor at the inlet which captures particles larger than the selected size. The SAME experiment included 2 DustTraks™ in separate enclosures. This made it possible to use one with a 1 µm impactor and one with a 10 µm impactor. The difference in the signal from these two devices provides a measure of the fraction of the particulate that was larger than 1 µm. In some cases dilution was required owing to the high smoke concentration levels.

As the aging chamber is filled and as the aerosol is pushed out to the moment instruments, a small aerosol stream is drawn off to the thermal precipitator, (Fig. 5). Inside the precipitator, the aerosol passes between a Transmission Electron Microscope (TEM) grid and a heated wire. Thermophoretic forces move particles to the grid surface where they adhere. After the mission the grids are removed from the assembly and examined in a TEM to obtain an independent determination of the particle size and morphology.

The smoke in the diagnostics duct is also sampled by an ISS smoke detector and a Space Shuttle smoke detector at the same time the moment instruments are making their measurements. These instruments are visible in Figure 3.

EXPERIMENTAL RESULTS

The system was installed in the Microgravity Science Glovebox, an ISS facility that provides many resources including: containment, power, data, video and uplink commanding. The hardware is shown installed in the MSG in Fig 6. Overall 30 sample materials were tested. These were comprised of six samples each of 5 materials: Teflon™, Kapton™, silicone rubber, cellulose, and dibutyl-phthalate deposited on a porous wick. These samples were tested at different airflow rates, pyrolysis temperatures, and smoke aging durations. The analog signals from the diagnostics were digitized at 1 Hz. Figure 7 contains the signal traces from a typical run for silicone rubber. The difference in the signals for the two DustTrak's indicates that a substantial portion of the aerosol mass is in particles that are larger than 1 µm. For comparison, Fig. 8 contains similar data for a Teflon run where little difference is evident between the two

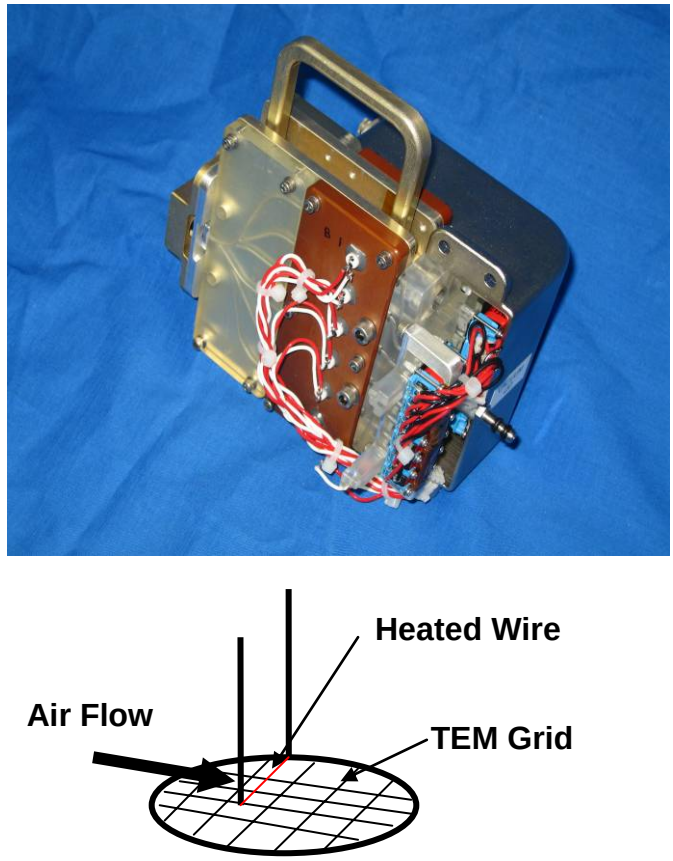

Figure 5: Thermal Precipitator Module. *Top image is a photograph of a partially disassembled Thermal Precipitator Module with the inlet manifold exposed on the left, the hot wire leads in the red Vespel block in the middle and the outlet valves on the right. The drawing below displays the position of the hot wire above the TEM grid with the air flow passing over both. The heated wire drives aerosol particles onto the grid via thermophoresis.*

DustTrak instruments, indicating that the bulk of the aerosol mass is in particles below 1 µm. The effect of aging is shown in Fig. 9 where, consistent with particle coagulation with limited wall loss, the overall number count (Ptrak) decreases substantially while the mass concentrations (DustTraks) remain relatively steady.

Figure 6: SAME Experiment installed in the MSG Facility.

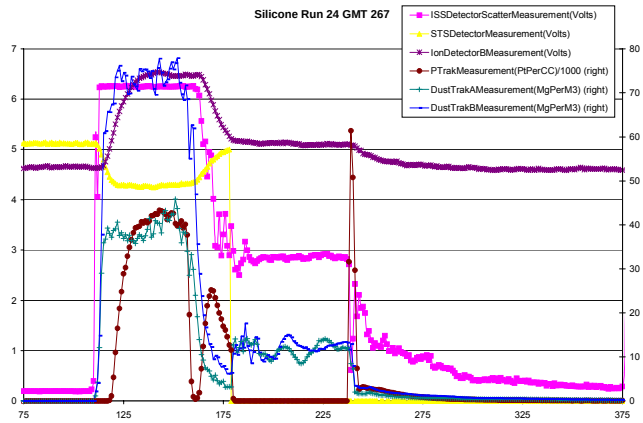

Figure 7: Instrument traces for a typical silicone rubber run. *Base levels are at the beginning and end of the trace. The actual sampling interval is between 125 and 160 seconds. The differences in the rise times of each instrument are due to the smoke transit time to the instrument. The large difference between DustTrak A and DustTrak B is indicative of the substantial portion of the particle distribution that is larger than 1µm (the cutoff for the impactor on DustTrak A).*

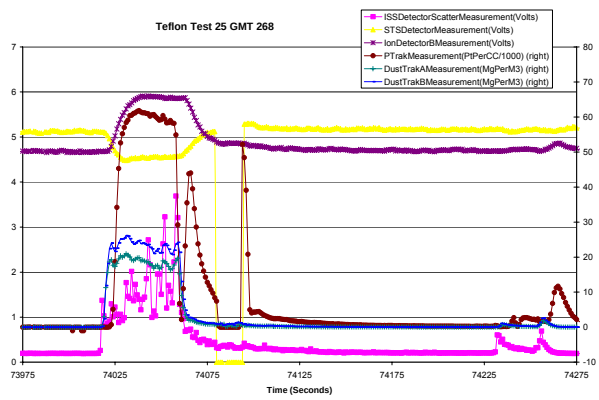

Figure 8: Instrument traces for a typical Teflon run. *Base levels are at the beginning and end of the trace. The actual sampling interval is between 74025 and 74060 seconds. The small difference between DustTrak A and DustTrak B is indicative that the most of the particle distribution is smaller than 1µm (the cutoff for the impactor on Dust Trak A).*

It is also interesting to compare the response of the ISS and STS detectors for silicone rubber and Teflon. In figure 7, both the ISS detector and the STS detectors show strong signals. (Note that the presence of smoke yields a positive deflection of the ISS signal and a negative deflection on the STS signal.) This is reasonable given the broader size distribution for silicone smoke containing significant numbers of both large and small particles. For the Teflon smoke comprised primarily of particles having diameters less than 1 micron as shown in figure 9, the STS detector provided a strong signal. Conversely, the signal from the ISS detector was more erratic. This will be re-visited after considering the preliminary data from the moment instruments.

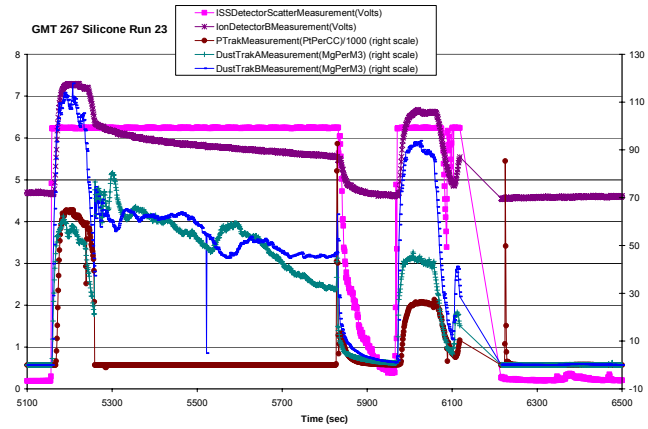

Figure 9: Instrument traces for a typical smoke aging run for silicone rubber. *Base levels are at the beginning and end of the trace. The first sampling interval is between 5200 and 5250 seconds and the post aging sampling interval is between 6000 and 6050 seconds. Consistent with particle coagulation with limited wall loss, the overall number count (Ptrak) decreases substantially while the mass concentrations (DustTraks) remain relatively steady.*

At this time the samples and TEM grids have been received back from the ISS; TEM and mass loss analyses have been initiated but not completed. Validation of the instrument calibration is underway and ground-based comparison (1-g) runs are being conducted. The zeroth and first moment instruments have a limited dependence on particle diameter so they may be directly calibrated. The third moment instrument (the DustTrak™) has a significant dependence on both the particle diameter and refractive index. An algorithm has been implemented to use the results of a Mie scattering calculation with the measured results to iteratively converge on the value of the third moment that best fits the DustTrak™ signal and the other two moment measurements. This third moment value will be used to compute the geometric mean diameters and standard deviations.

Average values of the count mean diameter for all of the unaged results for each material are tabulated in Table 1 along with the ratio of the signal from the two DustTraks. Recall that the impactor used in DustTrak A removed particles greater than approximately 1 micron; the impactor for DustTrak B removed particles greater than about 10 microns (although few particles greater than 10 microns should be present in these conditions). Although the count mean diameters are all in the 100 to 200 nm range, interpreting particle sizes by only one statistic can be deceptive due to the nature of the particle size distribution. In general, since the mass increases with the cube of the diameter, the larger particles do not affect the count mean diameter (CMD) as much as they affect the light scattering signal which scales with the particle mass. Consequently, although the CMD for silicone rubber is 227 nm, almost half the particle mass is larger than 1000 nm, as evidenced by the ratio of the DustTrak instruments. The lamp wick showed similar behavior.

Material	Count Mean Diameter (nm)	Ratio of DustTrak B/DustTrak A
Silicone Rubber	227	1.92
Teflon™	158	1.22
Lamp wick	172	1.79
Kapton™	128	1.26

Table 1: Average Count Mean Diameters and ratios of the Dust Trak instruments. *Dust Trak A had a 1 µm cutoff impactor while the cutoff for DustTrak B was 10 µm.*

On the other hand, the Kapton and Teflon showed substantially narrower particle size distributions with little mass in particles larger than 1000 nm. These low populations of larger particles are consistent with the less effective detection by light scattering devices which was seen for some of the Teflon tests and with the signals obtained from the STS and ISS detectors. All of the tests conducted in this series of experiments showed strong signals on the Space Shuttle detector (ionization) despite the larger particle size distributions seen for the lamp wick(cellulose) and silicone rubber. The CSD experiment [2] reported poor detection by the Space Shuttle detector for nonflaming overheat of cellulose and silicone rubber (indicating larger particle sizes). The reduced signal on the Space Shuttle detector for CSD suggests that under some reasonable pre-fire conditions the smoke size distribution can extend to diameters beyond those seen in the SAME experiment. The detection of smoke across the size range seen in SAME and CSD, while still discriminating against dust (which tends to be large) will probably require a detection system that can discriminate the particle size distribution to at least a limited degree. Two effective means of achieving this size discrimination are to employ a detector that measures more than one moment of the size distribution or to use a detector that can classify the particles into size ranges.

CONCLUSIONS

The SAME experiment operated successfully on the ISS during Increment 15. The preliminary results from the experiments indicate that substantial differences in the size distributions of the smoke particles are evident for the four materials that were tested. For the conditions of the SAME experiment, all samples produced significant numbers of sub-micron particulate that are better detected using an ionization smoke detector. Considering the results from both the SAME and CSD experiments, the only two fire detection experiments conducted in low-gravity, broader smoke particulate size distributions can be produced from credible pre-fire overheat events, depending on the conditions. These results suggest that detection methods that can measure more than one moment of the size distribution may show more successful detection and alarm rejection than single moment detectors.

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ACRONYNMS

CMD: Count Mean Diameter

CSD: Comparative Soot Diagnostics

DAFT: Dust Aerosol measurement Feasibility Test

ISS: International Space Station

MSG: Microgravity Science Glovebox

SAME: Smoke Aerosol Measurement Experiment

STS: Space Transportation System

TEM: Transmission Electron Microscope