Smoke Detection in Low Gravity – Results from the Smoke Aerosol Measurement Experiments (SAME) Conducted on the International Space Station

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The results are presented from tests that were conducted on the International Space Station (ISS) to evaluate the smoke particulate size for conditions that are representative of spacecraft fire scenarios. These tests included five materials typical of those found in spacecraft (Teflon, Kapton, cotton, silicone rubber and Pyrell) which were heated to temperatures below the ignition point. The conditions were controlled to produce repeatable smoke production levels. To achieve this the sample surface temperature and the air flow were controlled independently. Tests were conducted for each material at 2 or 3 surface temperatures and at air speeds ranging from quiescent to 8 cm/s. The effective transport time to the measurement instruments was varied from 11 to 800 seconds to simulate different smoke transport conditions in spacecraft. The aerosol properties were evaluated by three instruments which measured different moments of the particle size distribution. These moment diagnostics were used to determine the particle number concentration (zeroth moment), the diameter concentration (first moment), and the mass concentration (third moment). These statistics were combined to determine the diameter of average mass and the count mean diameter and by assuming a log-normal distribution, the geometric mean diameter and the geometric standard deviations were also calculated. Smoke particle samples were collected on TEM grids using a thermal precipitator for post flight analysis. The TEM grids were analyzed to determine the particle morphology and shape parameters. The different materials produced particles with significantly different morphologies. Overall the majority of the average smoke particle sizes were found to be in the 200 to 400 nanometer range with the quiescent cases and the cases with increased transport time typically producing substantially larger particles. The results varied between materials but the smoke particles produced in low gravity were approximately the same size as particles produced in normal gravity. These results can be used to establish design requirements for future spacecraft smoke detectors.

1. Introduction

Owing to the absence of low-gravity test data, spacecraft smoke detector systems for the ISS and the Space Shuttle were designed based on the properties of normal gravity smoke particulate and available technology at the time. Rational design selection of detection technology requires knowledge of both the expected signature of the events to be detected and the background levels of the measured parameters. Terrestrial fire detection systems have been developed based on extensive study of terrestrial fires [Bukowski, 1978 and 2003]. There are a number of factors that can be expected to affect the particle size distribution of the smoke from spacecraft fires. The absence of buoyant flow in low-gravity increases the residence time in microgravity fires and increases the transit time from the reaction zone to the detector [Brooker et al., 2007]. Microgravity fires have been found to have radically different structure from their normal-gravity (a.k.a. 1-g) counterparts. The limited options available to respond to a spacecraft fire increase the importance of early detection. Finally the materials used in spacecraft are different from typical terrestrial applications where smoke properties were previously evaluated. All of these effects could be expected to change the smoke particle size distribution. The objective of this work was to make sufficient measurements of smoke from spacecraft fires to enable improved design of future detectors.

Spacecraft Fire Detection Background

Prior spacecraft fire detection systems have been discussed in detail in papers by Friedman and Urban [Friedman, 1992, Urban et al., 2005]. In the Mercury, Gemini and Apollo missions, the crew quarters were limited and mission durations were short, consequently the mission design depended upon the crew to detect fires. The Skylab module, however, included approximately 30 UV-sensing fire detectors [Friedman, 1992]. These devices were limited to line-of-sight and were reported to have difficulties with false alarms. The Space Shuttle Detectors were based upon ionization fire detector technology, the most advanced technology available at the time and used an inertial separator designed to eliminate particles larger than 1-2 micrometers. The International Space Station (ISS) smoke detectors use near-IR forward scattering, rendering them most sensitive to particles larger than a micrometer, outside of the range of sensitivity of the shuttle detector. As described by Friedman [1992] there were six overheat and failed component events in the

NASA Orbiter fleet during its operational lifetime in addition to several similar incidents that have occurred on the ISS. 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 [Ruff, Urban and King, 2005]. 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.

2. Methods

The Smoke Aerosol Measurement Experiment (SAME) was developed to address this question by obtaining particulate size statistics on-orbit with a reduced dependence upon sample return to Earth. This is challenging because existing aerosol instrumentation is typically large, incompatible with spacecraft experiment constraints, and some systems 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 specifically the count mean diameter; the diameter of average mass; the geometric mean diameter; and the geometric standard deviation.

Instruments

These measurements were made using an assembly of three separate instruments. Two are industrial hygiene instruments manufactured by TSI™ and one is a modified residential smoke detector. More complete discussion of the SAME hardware is available in an earlier paper [Urban et al., 2008]. 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 region saturated with isopropanol vapor and then into a cooler region where the vapor condenses onto the particles increasing their diameter such that they can be 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 1 μm diameter. Some dilution is required, since the smoke concentration ranges from about 0.5×10^6 to 5×10^6 particles / cm^3. The dilution was accomplished by controlled addition of filtered nitrogen to the aerosol sample being directed to the P-Trak.

The first-moment instrument is the ionization chamber from a residential smoke detector. This device uses an alpha-particle emitter to generate ions in a region within a DC electric field. The drift of the ions in the electric field results in a current. The presence of aerosol particulate reduces the current as a result of the attachment of the ions to the particulate. The mobility of the charged aerosol is too small for it to be collected on the ionization chamber electrode. The required particle concentrations are on the order of 10^5 particles/cm^3 and no sample dilution was required.

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, as described in the calibration discussion below, additional compensation was employed to account for the range of materials and particle sizes that were seen in the SAME experiment. The device's operating range is from 0.001 mg/m^3 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-1 experiment included 2 DustTraks™ one with a 1 μm impactor and one with a 10 μm impactor. The difference in the signal from these two devices provided 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. A schematic of the assembled hardware appears in Fig. 1.

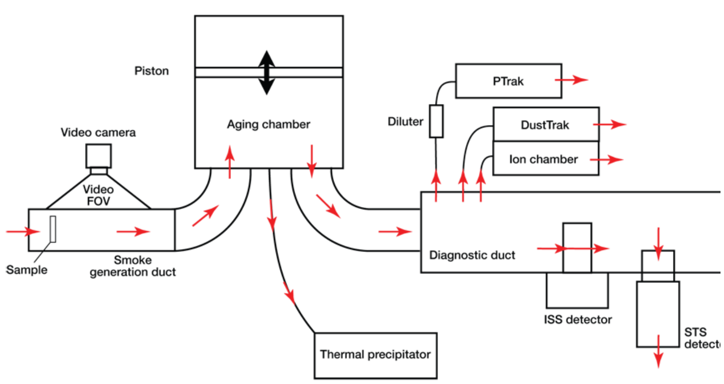


Figure 1. Schematic of the SAME hardware**.**

For SAME-2, one of the DustTrak devices was replaced by a new device, the MPASS (Multi-Parameter Aerosol Scattering Sensor), which is an optical scattering sensor that employs two detectors placed at fixed angles. The underlying design and performance have been reported previously [Greenberg and Fischer, 2010]. The basic configuration is similar to the DustTrak, however, the MPASS has two angles of detection and it can measure two approximate moment quantities specifically the 3rd and 2nd moments. Further, the optical geometry is optimized using a Mie-scattering model for aerosols with light scattering properties typical of smoke: i) geometric mean diameters from 0.1 – 1.0 microns; ii) geometric standard deviations of 1.6 – 1.9; iii) the aerosols have lognormal size distributions and vi) a fixed, real value for refractive index of 1.6. This device was included as a technology demonstration of an aerosol sensor that measures two moments simultaneously. The underlying assumption is that by measuring two moments of the aerosol it is possible to correct the smoke detector signal for the particle size, unlike previous spacecraft smoke detectors which are limited to a single moment measurement [Urban et al., 2008]. This will enable the alarm to be less sensitive to larger particles that are typical of dust. The relative advantage of this approach was discussed in more detail in a prior paper [Urban et al., 2009].

3. Results and Discussion

Over 100 sample materials were tested. These were comprised of samples of 6 materials: Teflon™, Kapton™, Pyrell™, silicone rubber, cellulose (lampwick), and dibutyl-phthalate deposited on a porous wick. The test conditions included multiple sample temperatures and air flow rates. The baseline air flow rate was 8 cm/s with runs conducted at rates down to 2 cm/s with a limited set conducted with no airflow while the sample was heated. The sample temperatures were based on the pyrolysis properties of the material and were thus material specific. The baseline temperature was selected to produce 1 to 2 mg of weight loss in 60 seconds and have reasonable signal on each of the moment instruments. To examine the effect of sample temperature, additional higher temperature conditions were also selected that would not saturate the moment instruments. The TEM grids recovered from the thermal precipitators on SAME-1 were unfortunately contaminated with extraneous which rendered the grids unusable. For SAME-2 more rigorous assembly controls were followed and numerous good particle images were obtained. For typical runs, the particle concentrations were a few million particles / cc and the mass concentrations were 2 to 15 mg/m^3; however there were runs with fewer particles. For these conditions, the typical numbers of particles sampled by the instruments were in the billions although for the test with the lowest particle concentrations the sample sizes were of the order of several million particles.

Moment Instrument Results

Geometric mean, count mean, and average mass diameter results from the moment instruments for baseline runs are presented in Table 1 [Urban et al., 2012]. As described above, calculation of the count mean diameter and the diameter of average mass is independent of the nature of the size distribution; whereas the assumption of a log-normal distribution is implicit in the calculation of the geometric mean diameter and the geometric standard deviation (σ_g). This assumption cannot be directly tested with the available data since this would require a device that can separate the particles into size bins. This assumption has been examined for normal-gravity smoke produced from these materials using the same heating process as the space flight experiment [Meyer et al., 2103] with good results. Furthermore, there are two indications that the distribution can be approximated by a log-normal distribution. In the cases listed below, the count mean diameter is less than the diameter of average mass which is a necessary condition for a log-normal distribution. The second indication is that the geometric standard deviations are all physically reasonable (i.e. greater than 1 and less than approximately 3.5 which is the practical limit on the magnitude of aerosol geometric standard deviation). The aging results show a substantial increase in the observed diameters. As expected the increase in the count mean diameter is greater than the corresponding increase in the diameter of average mass. This can be understood since coagulation consists of particle collisions joining two particles. For a polydisperse aerosol, these collisions usually involve the collision of one of the smallest (high mobility) particles with the largest (high cross-section) particles. This collision has little effect on the size of the large particle but it removes the smaller particles from the size distribution. This has a larger effect on the count mean diameter since it is linear in diameter while the diameter of average mass varies with the cube root of the diameter. Theoretical predictions suggest that this process will produce a near lognormal distribution and that the standard deviation will tend toward a self-preserving distribution with a value of 1.32 [Hinds, 1999].

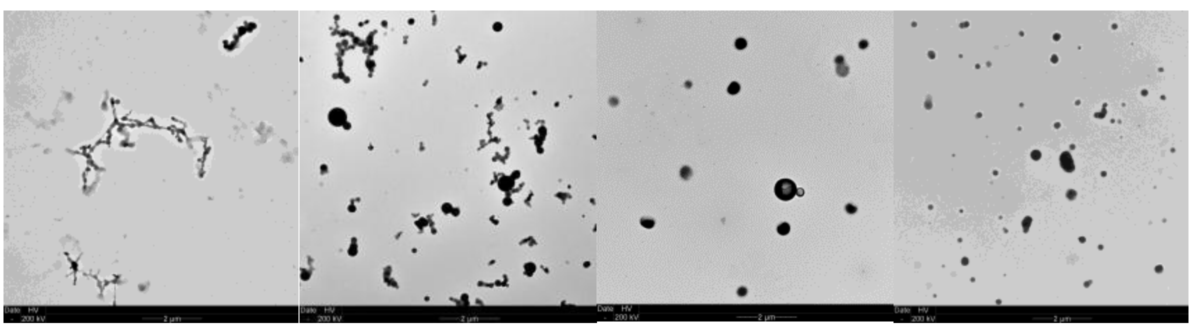
Overall, the Teflon and Kapton particles were very small. The lampwick, Pyrell, and silicone results exhibited substantially larger diameters of average mass, particularly for the aged cases. The comparatively smaller diameters for the Kapton and Teflon will make detection of this smoke challenging for light scattering devices, on the other hand the large sizes seen with the lampwick and silicone would generate very large signals on a light scattering system. As discussed by Urban et al. [2009], some level of particle size discrimination is generally required to have a system that is sensitive enough to trigger an alarm for the low signal from small particles such as Teflon and Kapton without excessive nuisance alarms from large dust particles. This suggests that detection of these particles against the background environment will be facilitated by a detection system capable of measuring more than one moment of the particle size distribution.

		Geometric Mean Diameter (Dg) (µm)	Count Mean Diameter (M_1/M_0) (µm)	Diameter of Average Mass (M_3/M_0) (µm)	σ_g
Kapton	Unaged	0.042	0.056	0.101	2.154
	Aged 720 s	0.089	0.109	0.161	1.872
Lampwick	Unaged	0.090	0.128	0.258	2.312
	Aged 720 s	0.229	0.276	0.398	1.834
Silicone	Unaged	0.128	0.196	0.465	2.530
	Aged 720 s	0.269	0.355	0.619	2.108
Teflon	Unaged	0.081	0.101	0.170	2.198
	Aged 720 s	0.070	0.105	0.232	2.442
Pyrell	Unaged	0.149	0.204	0.384	2.211
	Aged 720 s	0.293	0.359	0.539	1.892

Table 1: Diameter results for baseline runs for each material (Diameters are in micrometers).

TEM Results

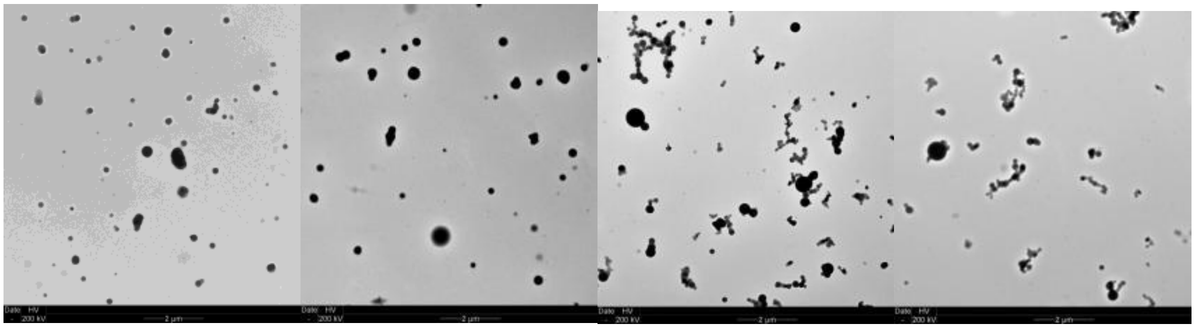
Overall, 72 particle samples were taken on Transmission Electron Microscope (TEM) grids using the thermal precipitator. These samples were imaged with a TEM to evaluate the particle morphology as a function of flow conditions, material and heating level. Silicone rubber and DBP presented no particles that were visible via TEM, presumably because the particles were condensed liquid that evaporated before they could be imaged in the TEM. Figure 2 presents typical images for the major materials.



Length scale 2 µm

Figure 2: TEM images for Teflon (Run 56), Pyrell (Run 63), Lampwick (Run 54) and Kapton (Run 62).

As seen in Table 1, aging did increase the average particle size, however this level of change is not readily visible in the TEM images, instead the most visible change is the disappearance of the smallest particles. (Fig 3) As described in the discussion of Table 1, this is consistent with expectations since the smaller particles have the highest mobility and consequently are readily incorporated into the larger particles. Particularly for the semi-liquid particles, this absorption of the smallest particles into larger particles is expected to have little or no apparent effect on the size of the larger particles because the diameter is the cube root of the volume. In the case of non-liquid particles, the smallest particles will nevertheless be unlikely to be visible via TEM when they are attached to larger particles.



Length scale 2 µm

Figure 3: TEM images showing the effect of aging for Kapton (Run 62) and Pyrell (Run 63). From Left to right: unaged Kapton, aged Kapton, unaged Pyrell, and aged Pyrell. The notable change is the elimination of the smallest particles.

4. Conclusions

The SAME experiment produced repeatable measurements of smoke particulate from 5 materials typical of those found in spacecraft. From these results the following observations can be made:

1. For the conditions of the SAME experiment, all samples produced significant numbers of sub-micron particulate that are readily detected using an ionization smoke detector.
2. Particle sizes ranged from 100 to 600 nm and the measured parameters were consistent with a log-normal distribution.
3. Consistent with expectation, particle sizes increase substantially with aging. These results suggest that some materials such as silicone rubber can produce smoke that can reach sizes better detected by light scattering techniques.
4. Particle dimensions increase substantially as air flow was decreased. The zero flow conditions produced smoke particles that were as much as 2 to 3 times larger than those produced at the nominal 8 cm/s flow rate.
5. TEM samples demonstrated a significant range of particle morphologies with materials typically having distinct morphologies. The exception being Pyrell particles collected under zero airflow conditions where the particles coalesce rather than aggregating as they did at higher air flows.

Since spacecraft fire conditions include an even wider array of materials than those tested here and a broader range of flow and temperature conditions, broad smoke aerosol size distributions can be expected from credible pre-fire overheat events. These results suggest that detection methods that can measure more than one moment of the size distribution may show more successful detection and false alarm rejection than single moment detectors.

Acknowledgements

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