

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.

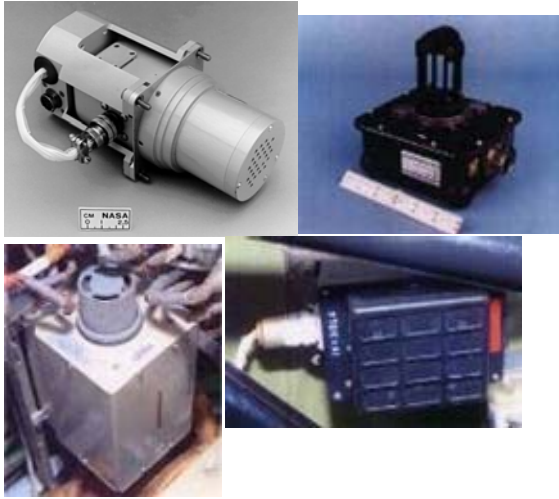


Figure 1: Current Spacecraft smoke detectors.
Clockwise from top left: ionization smoke detector used in the NASA Orbiter fleet; light scattering detector used in the US lab on the ISS; ionization detector used in the Russian ISS Service Module; and ionization detector used in the Russian ISS FGB Module.

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 $0.3\ \mu\text{m}$. 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 $1\ \mu\text{m}$ 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 $\sim 40\%$ of the particles in each of the 2.5 to $10\ \mu\text{m}$ and $>100\ \mu\text{m}$ ranges. The other two ranges $<2.5\ \mu\text{m}$ and 10 to $100\ \mu\text{m}$ 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 $<2.5\ \mu\text{m}$ 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 the mass, surface area, and volume 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 0.3λ to about 3λ (~ 0.2 to $2.0 \mu\text{m}$ 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 $\bar{d}$, which is equal to M_1/M_0 and the diameter of average mass $D_{1.5}$ or d_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

$$\ln D_g = \frac{\int_0^\infty \ln D f_N(D) dD}{\int_0^\infty f_N(D) dD} \quad (4)$$

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

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 $D_g = 1.0 \mu\text{m}$ and $\sigma_g = 2.0$, the corresponding values of $D_{0.5}$ and $D_{1.5}$ are $1.27 \mu\text{m}$ and $2.06 \mu\text{m}$, respectively. Using equation (6), one can relate σ_g to the ratio of $D_{1.5}$ and $D_{0.5}$ via the equation:

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

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

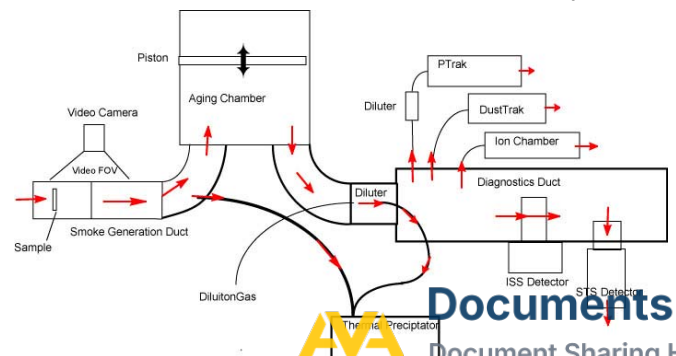


Figure 2. Schematic of the SAME hardware.