Spacecraft Smoke Detector Characterization with Reference and Smoke Aerosols

Xiaoliang Wang[1], Judith C. Chow[2], and John G. Watson[3]
Desert Research Institute, Reno, NV 89512, USA

Marit E. Meyer[4] and Gary Ruff[5]
NASA Glenn Research Center, Cleveland, OH 44135, USA

John Easton[6]
Case Western Reserve University, Cleveland, OH, 44106, USA

Gordon Berger[7]
Universities Space Research Association, Cleveland, OH 44135, USA

and

Paul D. Mudgett[8]
NASA Johnson Space Center, Houston, TX 77058, USA

Performance testing of consumer smoke detectors requires specific facilities and experiments with smoldering and flaming emissions from different fuels. Smoke detectors for use in spacecraft are tested using similar setups with representative fuel materials. To simplify smoke detector testing, this study explored the use of laboratory-generated reference aerosols as transfer standards to evaluate smoke detector performance. Among the three tested reference aerosols, mineral oil particles were reproducibly generated with a Gemini smoke detector tester, dioctyl sebacate (DOS) particles were generated with a wide concentration range and flexible size distributions using an atomizer, while polystyrene latex (PSL) particles were difficult to produce with the high concentrations needed for smoke detector testing. Reference aerosols generated from 1.5%–100% DOS solutions and mineral oil covered the response range of six types of smoke aerosols generated by oxidative pyrolysis of spacecraft-relevant materials. Although no single reference aerosol can be used to simulate the response of different smoke detection technologies to different smoke aerosols within ±10% error, the relationship between reference and smoke aerosols derived from this study can be used to predict smoke detector responses to combustion aerosols.

Nomenclature

ASTM	=	American Society for Testing and Materials
CO	=	Carbon monoxide
CO_2	=	Carbon dioxide

---

[1] Research Professor, Division of Atmospheric Sciences, 2215 Raggio Pkwy, Reno, NV 89512.
[2] Research Professor, Division of Atmospheric Sciences, 2215 Raggio Pkwy, Reno, NV 89512.
[3] Research Professor, Division of Atmospheric Sciences, 2215 Raggio Pkwy, Reno, NV 89512.
[4] Research Aerospace Engineer, Low-Gravity Exploration Technology Branch, 21000 Brookpark Road, Cleveland, OH 44135.
[5] Project Manager, Spacecraft Fire Safety Demonstration Project, 21000 Brookpark Road, Cleveland, OH 44135.
[6] Associate Staff Scientist, Mechanical and Aerospace Engineering, 10900 Euclid Ave., Cleveland, OH, 44106.
[7] Physical Scientist, MS 110-3, 21000 Brookpark Road, Cleveland, OH 44135.
[8] Environmental Scientist, M/C SK4, 2101 NASA Pkwy, Houston, TX 77058.

COV	=	Coefficient of variation
CSP	=	Commercial Space Prototype
DMA	=	Differential mobility analyzer
DOS	=	Dioctyl sebacate
Dp	=	Particle mobility diameter
GASP	=	Gases and Aerosols from Smoldering Polymers
GRC	=	Glenn Research Center
Hz	=	hertz, frequency unit
ISS	=	International Space Station
NASA	=	National Aeronautics and Space Administration
PMMA	=	Poly(methyl methacrylate)
PSL	=	Polystyrene latex
PTFE	=	Polytetrafluoroethylene
SMPS	=	Scanning mobility particle sizer
STS	=	Space Transport System
N	=	Particle number concentration
$PM_{2.5}$	=	Particulate matter with aerodynamic diameter ≤2.5 μm
UL	=	Underwriters Laboratories
WCPC	=	Water condensation particle counter

I. Introduction

IN the United States, performance of consumer smoke detectors is regulated according to the Underwriters Laboratories Standard for Smoke Alarms (UL217),[1] which outlines tests, facilities, and experiments with smoldering and flaming emissions generated from different fuels. Although there is no established standard for spacecraft smoke detectors, they have been tested using similar methods with fuels representative of materials used in spacecraft. To reduce the level of effort required to test smoke detectors and predict performance of future smoke detector designs, laboratory-generated reference aerosols can be used as transfer standards. Compared to smoke aerosols, reference aerosols can be generated with more precisely controlled chemical composition, size distribution, concentration, and optical properties. They can be used to challenge smoke detectors with controllable and reproducible test conditions. Once relationships between smoke detector responses to reference and smoke aerosols are established, smoke detector responses to reference particles can be used to simulate their responses to smoke aerosols. Specific objectives of this study are to: (1) evaluate a method to test smoke detectors using reference aerosols with controlled size distributions and concentrations, (2) characterize smoke detector responses to reference and combustion aerosols, and (3) determine the feasibility of using reference aerosols to predict smoke detector responses to different types of smoke aerosols.

II. Material and Methods

A. Experimental Setup

The experiments were conducted in the Gases and Aerosols from Smoldering Polymers (GASP) Laboratory at the National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC).[2] A schematic diagram of the experimental setup is illustrated in Figure 1, which includes aerosol generators, a smoke chamber, smoke detectors, and aerosol characterization instruments.

Reference aerosols were generated by three aerosol generators: a constant output atomizer (Model 3076, TSI Inc.), a six-jet atomizer (Model 9306, TSI Inc.), and smoke detector tester (Model 501B, Gemini Scientific Corporation). When particles were generated from a liquid suspension or solution, the solvent vapor was removed by a diffusion dryer (filled with silica gel to remove water vapor or activated charcoal to remove alcohol vapor). A dilution bridge, consisting of one path with a filter and a valve to remove particles and another path with a valve to adjust the undiluted aerosol flow rate, was used to adjust the aerosol concentration. Dried and diluted (when necessary) particles were injected into a 326-L acrylic-walled smoke chamber, where a mixing fan promoted concentration uniformity.

Smoke particles were generated by a tube furnace (Lindberg/Blue M). Fuel samples were loaded in a 9-cm-long alumina boat at room temperature. The boat was then placed inside a quartz tube and inserted to the optimal heating zone of the tube furnace. The temperature of the furnace was ramped to preset values chosen for thermal oxidative decomposition of each fuel material. Filtered air flowed through the tube furnace at 4.4 L/min to flush the pyrolysis products into the smoke chamber.

Smoke obscuration level in the chamber was measured with an obscuration meter based on American Society for Testing and Materials (ASTM) E662-17A.[3] The light source and detector covered a broadband wavelength from 400 to 2200 nm. A Commercial Space Prototype (CSP) smoke detector based on light scattering was co-located with a commercial ionization smoke detector (referred to as IonZG), and their analog output voltages were logged at 10 Hz. Two consumer smoke alarms, one ionization type (Model I12010S, Kidde) and one light scattering type (Model P3010H, Kidde), were used for comparison. Because their raw analog signals were not accessible, only the alarm voltages were logged.

Portions of the test aerosol were extracted from the chamber through two separate sampling lines and directed to several instruments. A DustTrak DRX (Model 8534, TSI Inc.) measured size-segregated particulate matter (PM) mass concentrations (i.e., PM_1, $PM_{2.5}$, PM_4, PM_{10}, and PM_{15}) based on laser (655 nm) light scattering.[4-6] Most combustion generated aerosols are in the $PM_{2.5}$ size fraction. Due to its fast response (every 1 s), high sensitivity (1 μg/m^3), and wide dynamic concentration range (0–600 mg/m^3), the DRX reading was used as an aerosol concentration reference to compare smoke detector responses to different aerosols. Note that the mass concentrations reported by the DRX can differ from gravimetric mass concentrations depending on particle size distribution, composition, and refractive index. During polydisperse reference aerosol tests, a scanning mobility particle sizer (SMPS; Model 3938, TSI Inc.)[7] measured particle size distributions every 135 s. The aerosol and sheath flow rates were 0.52 and 3 L/min, respectively, resulting in a measured size range of ~0.01–0.7 μm in 108 equally spaced channels on a logarithmic scale. During monodisperse reference aerosol tests, a differential mobility analyzer (DMA; Model 3081, TSI Inc.)[8] classified particles based on electrical mobility and a water condensation particle counter (WCPC; Model 3787, TSI Inc.)[9] measured the monodisperse particle number concentrations. Due to fast changing particle size distributions, the SMPS was not used during smoke tests. A second aerosol stream was directed to a light scattering smoke detector used in the International Space Station (ISS) and an ionization smoke detector used in the Space Transport System (STS) fleet.[10] Neither the ISS scatter nor STS ion detector is equipped with a pump; a fan at the end of the sampling line drew the aerosol through these two detectors. Due to potential aerosol concentration inhomogeneity in the smoke chamber, different time for aerosols to reach detectors, and different detector response time, all detectors responded to aerosol concentration changes at different speeds. To account for these differences, time series of detector responses were aligned by maximizing the correlation coefficients of regression between the detector and DRX responses.

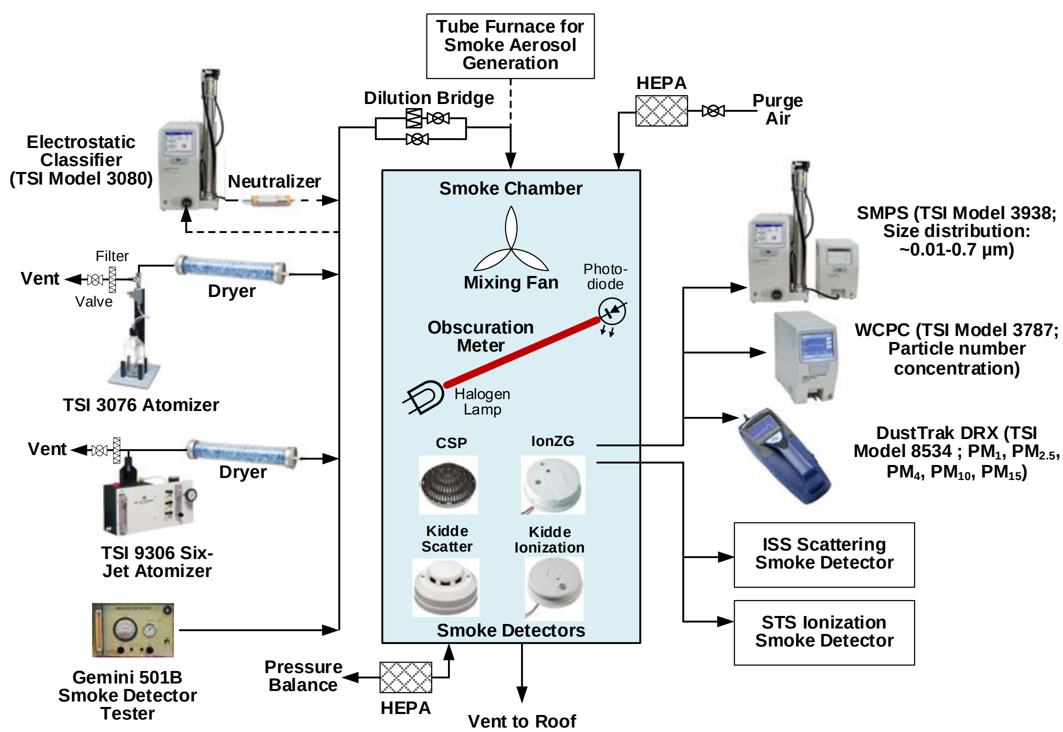


Figure 1. Experimental setup for smoke detector evaluation.

Each sampling day started with a ~5-minute background measurement after the smoke chamber was purged with filtered air to concentrations ≲20 particle/cm^3. Instrument baselines were also measured at the beginning of each test before aerosols were delivered into the smoke chamber. After the aerosol test was completed and aerosol generation ended, the chamber was purged with clean air. In most tests, data from all instruments were logged until the concentration returned to the baseline.

B. Reference Aerosol Materials and Generation

Three types of reference aerosols were generated using three different generation techniques:

- Refined mineral oil (Rudol®) has a nominal density of 0.861 g/cm^3 and a refractive index of 1.470. It is used in the Gemini 501B smoke detector tester for smoke detector inspection and sensitivity test. Polydisperse mineral oil particles were generated by the Gemini 501B on three different days using similar settings to test reproducibility of particle generation and smoke detector responses.
- Dioctyl sebacate (DOS) particles are spherical with a density of 0.915 g/cm^3 and a real refractive index of 1.448. The size distribution of DOS particles can be adjusted by changing the DOS solution concentration. Four DOS solution concentrations (i.e., 1.5%, 5%, 40%, and 100%) in isopropyl alcohol were used to generate polydisperse DOS particles with different mode diameters by the TSI 3076 atomizer. Monodisperse DOS particles were also generated by size selection using a DMA. Monodisperse 100 nm and 200 nm particles were generated from the 1.5% DOS solution, while 300–700 nm particles were generated from the 40% DOS solution. However, it was difficult to generate high concentrations of <500 nm monodisperse particles to produce smoke detector signals.
- Polystyrene latex (PSL) spheres are commonly used as particle size standards. PSL particles have well defined sizes, density (1.05 g/cm^3), and refractive index (1.590). Attempts were made to generate monodisperse PSL particles (300 nm, 500 nm, and 900 nm) by the TSI 3076 and 9306 atomizers with and without DMA size classification. However, the particle concentrations were too low to generate reliable smoke detector signals. Therefore, the PSL data are not presented in this paper.

C. Smoke Aerosol Materials and Generation

Six types of materials relevant to spacecraft safety were tested and their photographs before and after pyrolysis are shown in Figure 2.

- Cotton lamp wick represents cellulose materials such as paper, wood, and fabrics. Thermal decomposition of cellulose emits carbon monoxide (CO), carbon dioxide (CO_2), tar, and char. Three lamp wick tests utilized 0.75–1 g mass each with the furnace temperature set to 200–240 °C.
- Kapton, a polyimide film with chemical formula $(C_{22}H_{10}N_2O_5)_n$, is stable across a wide range of temperatures (~-269–400 °C). Kapton is used in thin-film heaters, wire insulation, space suits, tape and multi-layer insulation. Kapton thermal decomposition results in liquid aromatic products and spherical particles. Three Kapton tests utilized 1–2 g mass each with the furnace temperature set to 450–500 °C.

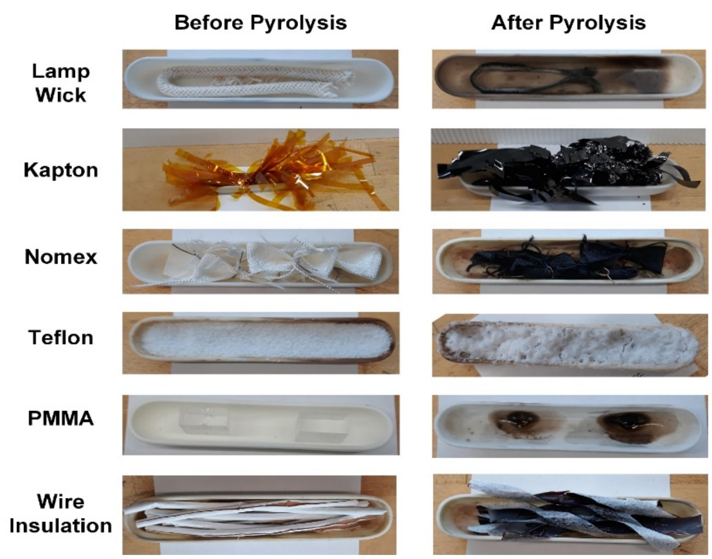


Figure 2. Photograph of several fuel samples before and after pyrolysis in the tube furnace.

- Nomex® is a heat and flame-resistant woven textile used for cargo bags, thermal blankets, acoustic insulation, and pressure suits. When heated, it liberates CO, CO_2, hydrogen cyanide, and organic species, leaving a carbon-rich char. Three Nomex tests utilized 0.5–1 g mass each with the furnace temperature set to 350–400 °C.

- Teflon is a brand name of polytetrafluoroethylene (PTFE, $(C_2F_4)_n$), a fluoropolymer commonly used for wire insulation, water storage bladders, sampling bags, suits, and cargo liners. Teflon releases polymer fragments during thermal decomposition which grow into particles through nucleation, condensation, and coagulation. Three Teflon tests utilized ~8 g mass each with the furnace temperature set to 400–500 °C.
- Poly(methyl methacrylate) (PMMA; also known as Plexiglas or acrylic glass), with a chemical formula of $(C_5O_2H_8)_n$, is a window material for spacecraft components. During smoldering combustion, PMMA undergoes thermal oxidative decomposition, generating odorous monomers and other volatile organic compounds (VOCs), as well as CO and CO_2. One PMMA test was conducted using 2 g mass with the furnace temperature set to 200 °C.
- Fluoropolymer (FP)/polyimide (PI) wire insulation is a potential source of smoke in spacecraft due to thermal degradation caused by wire overheating. One wire insulation test was conducted using 2 g mass with the furnace temperature set to 450 °C.

III. Results and Discussion

A. Polydisperse Mineral Oil Particles and Smoke Detector Signal Reproducibility

Polydisperse mineral oil particles were generated on three different days (5/14/2019, 5/17/2019, and 5/23/2019) to evaluate the reproducibility of particle size distributions and smoke detector responses. Figure 3a shows that mineral oil particles generated on two separate days had similar number size distributions (expressed as normalized concentration per diameter channel width on a logarithmic scale [dN/dlogDp] as a function of diameter [Dp]). The mode diameters (385 nm and 346 nm) differed by ~10% whereas the geometric standard deviations (1.37 and 1.36) were nearly identical. The Gemini 501B was able to generate mineral oil particles with reproducible size distributions.

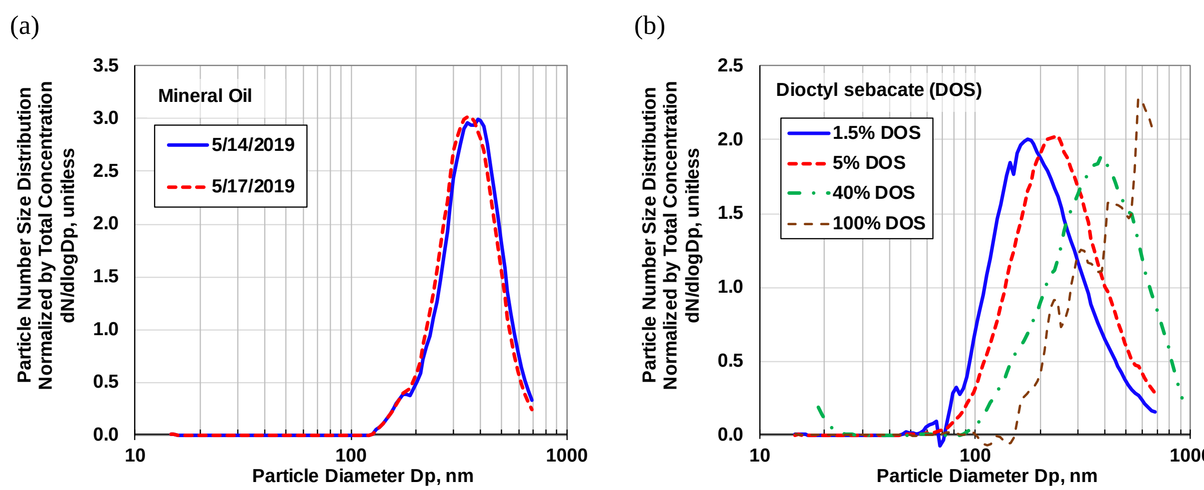


Figure 3. Normalized particle number size distribution for: (a) polydisperse mineral oil particles generated by the Gemini 501B smoke detector tester on two different days (size distributions were not measured on 5/23/2019); and (b) DOS particles generated from four DOS solutions with different concentrations.

Figure 4 compares smoke detector responses as a function of mineral oil particle concentrations on three different days. Figure 4a shows that the CSP detector signal increased linearly with DRX $PM_{2.5}$ concentrations over a wide range of ~1–160 mg/m^3, with linearity down to < 1 mg/m^3. The regression slopes on 5/17/2019 and 5/23/2019 were almost identical, but were ~20% higher than the slope for the 5/14/2019 test. The slightly different particle size distributions in Figure 3a might have contributed to the slope differences between 5/14/2019 and 5/17/2019. Within experimental uncertainties, the three slopes are deemed equivalent, with average ± standard deviation values of 0.0108±0.0013. The linearity and high correlation between the CSP detector and DRX are expected because both devices are based on light scattering. The CSP detector is shown to generate repeatable responses to mineral oil particles during tests on different days.

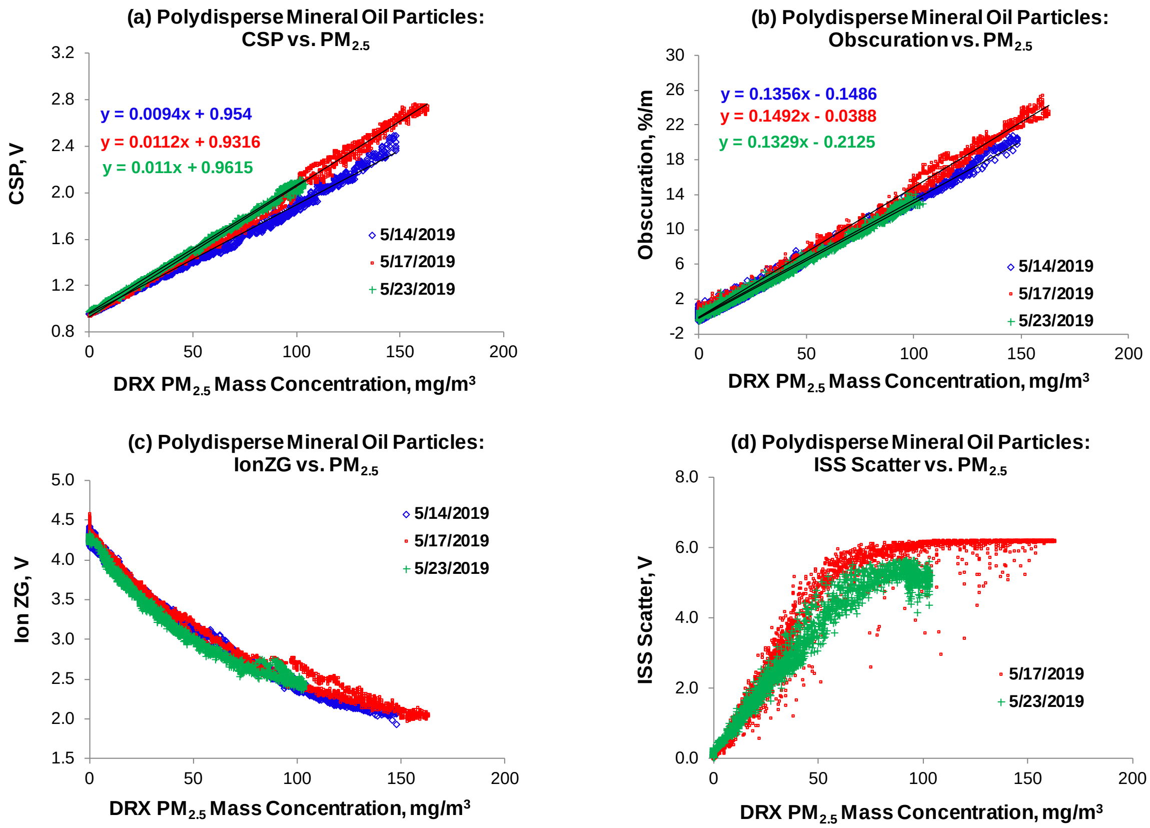


Figure 4. Variation of smoke detector responses as a function of DRX $PM_{2.5}$ mass concentration for polydisperse mineral oil particles generated by the Gemini 501B smoke detector tester on different days.

Figure 4b shows that obscuration increased linearly with DRX $PM_{2.5}$ concentrations of ~5–200 mg/m^3 for mineral oil particles. The obscuration meter signal-to-noise ratio decreased for concentration $\lesssim$5 mg/m^3. The linear regression slopes from tests on three different days were similar, with an overall slope of 0.145±0.011 and a coefficient of variation (COV) of 6.3%.

Figure 4c shows that the IonZG smoke detector signal decreased nonlinearly with increasing DRX $PM_{2.5}$ concentrations. Similar responses were found for the three tests. The radioactive sources in ionization smoke detectors ionize air and generate an ion current, which decreases when smoke particles are present. Working on the same principle, the STS ion detector signal also decreased nonlinearly with increasing $PM_{2.5}$ (not shown).

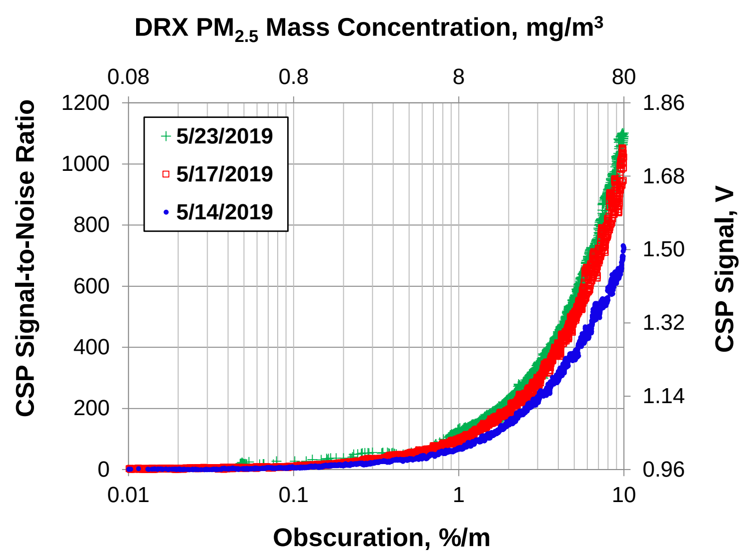


Figure 5. The CSP detector signal-to-noise ratio as a function of obscuration and DRX $PM_{2.5}$ mass concentration for polydisperse mineral oil particles.

The ISS scatter detector results were invalidated during the 5/14/2019 tests due to a leak in the transfer line, and only the 5/17/2019 and 5/23/2019 data are plotted in Figure 4d. The ISS scatter detector showed similar variation with DRX $PM_{2.5}$ concentrations between the two tests: the signal increased linearly up to ~4 V at DRX $PM_{2.5}$ concentrations of ~50 mg/m^3 and saturated at ~6 V with higher $PM_{2.5}$ concentrations ($\gtrsim$70 mg/m^3).

The CSP detector signal-to-noise ratios as a function of obscuration level is shown in Figure 5. The x-axis is plotted on a logarithmic scale to better illustrate detector signal changes at lower obscuration levels. The signal-to-noise ratios were ~73–110 at 1%/m obscuration and ~755–1125 at 10%/m obscuration, indicating reasonable sensitivity of the CSP detector for polydisperse mineral oil particles. The CSP detector used a narrow voltage range for smoke detection: ~0.96 V at 0%/m obscuration, $\lesssim$1.2 V at 3%/m obscuration, and $\lesssim$ 3 V at 30%/m obscuration. Although the signal-to-noise ratio was high (>50) at 1%/m obscuration, the signal resolution and reliability would be enhanced by increasing the dynamic range of the CSP detector signal within the obscuration range of interest for smoke detection.

In summary, tests on three days over a 10-day period shows that the Gemini 501B smoke detector tester was able to generate polydisperse mineral oil particles with reproducible size distributions and that the smoke detectors showed reproducible responses as a function of the DRX $PM_{2.5}$ concentrations.

B. Polydisperse DOS Particles and Smoke Detector Responses

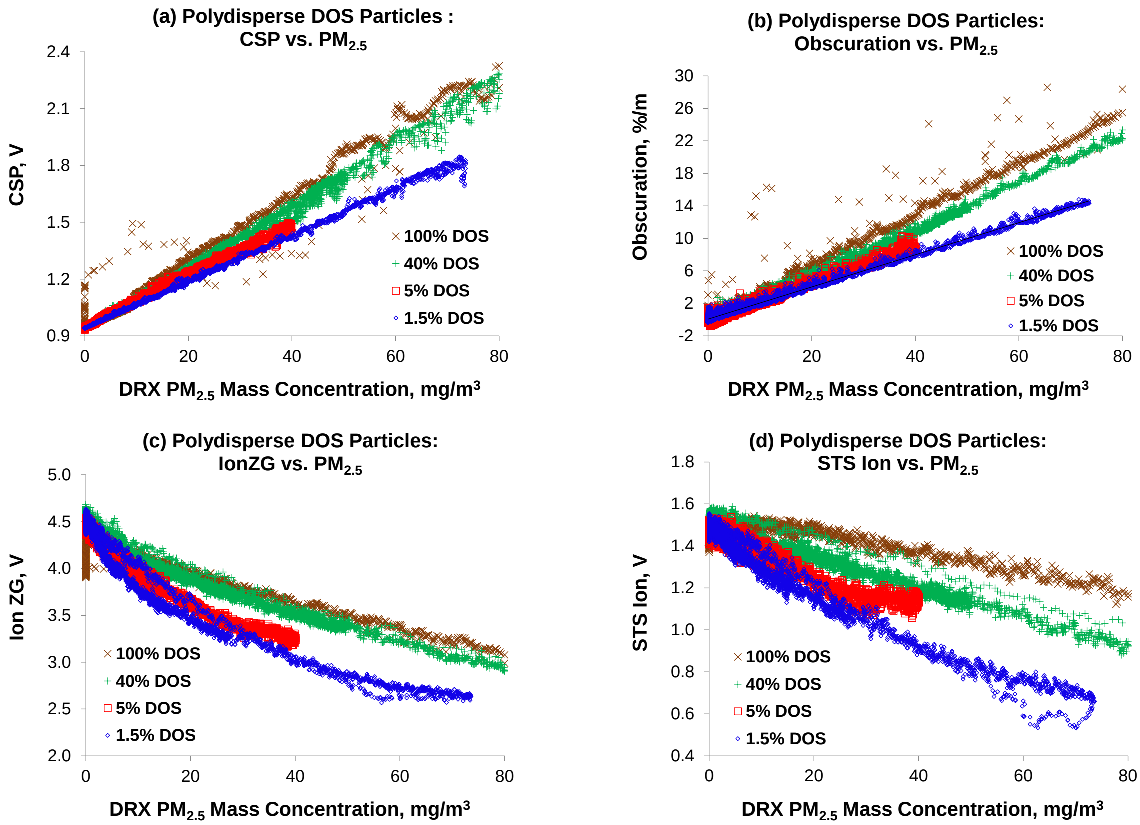
The advantage of using an atomizer to generate DOS reference aerosols is that particle size distributions can be adjusted by changing the solution concentration. Assuming that the atomizer generates the same droplet diameter with different solution concentration, the conservation of solute mass indicates that the mean particle diameter would be approximately linearly proportional to solution concentration to the 1/3 power. Figure 3b shows representative particle number size distributions (normalized by total measured concentrations in each SMPS scan) for polydisperse DOS particles generated from four solution concentrations. As expected, the mode (peak concentration) diameter increased with DOS concentration. The size distributions were approximately lognormal, with geometric standard deviations of 1.6–1.7, wider than those for mineral oil particles (1.36–1.37 in Figure 3a). The mode diameters were: 175, 241, 385, and $\gtrsim$ 600 nm for 1.5%, 5%, 40%, and 100% DOS solutions, respectively. The SMPS did not cover the full distribution for the 100% DOS, resulting in an inaccurate size distribution due to inaccurate multiple charge corrections.

Smoke detector responses as a function of DRX $PM_{2.5}$ concentration for polydisperse DOS particles from the four solution concentrations are compared in Figure 6. Figure 6a shows that the CSP detector voltage signal increased linearly with DRX $PM_{2.5}$ concentrations. The linear regression slope increased slightly with particle size: 0.0122, 0.0134, and 0.0166 for 1.5%, 5%, and 40% DOS concentrations, respectively. The slope for 100% DOS concentration (0.0155) was somewhat lower than, but similar to, that for the 40% DOS concentration. The CSP detector linearity covered a wide range of DRX $PM_{2.5}$ concentrations from <1 mg/m^3 to ~200 mg/m^3. At high concentrations of >300 mg/m^3, the signal started to saturate at ~5–8 V. The CSP vs. DRX relationships had higher variability for DOS particles in Figure 6a than those for mineral oil particles in Figure 4a. This is probably due to the different optical designs (e.g., light source wavelength and scattering angle) of the CSP and DRX, which caused their light scattering responses to be different for different size distributions.

Figure 6b shows that obscuration meter response was also linearly related to DRX $PM_{2.5}$ concentrations. Similar to the CSP detector, the linear regression slope increased slightly with particle size: 0.198, 0.225, 0.280, and 0.312 for 1.5%, 5%, 40%, and 100% DOS concentrations, respectively. The linearity extended to a wide DRX $PM_{2.5}$ concentration range of ~5–200 mg/m^3.

Similar to mineral oil particles, Figure 6c shows that the IonZG smoke detector signal decreased nonlinearly with increasing DRX $PM_{2.5}$ concentrations. It had good signal-to-noise ratios for concentrations $\gtrsim$ 2 mg/m^3. The response per mass concentration was larger for smaller particles (1.5% and 5% DOS concentrations) than larger particles. This is expected because for the same aerosol mass concentration, ionization smoke detectors are more sensitive to smaller particles. On the other hand, the DRX based on light scattering is less sensitive to particles $\lesssim$300 nm, and it may underestimate $PM_{2.5}$ mass concentration for smaller particles. Figure 6d shows that the STS ion detector signal decreased approximately linearly with increasing DRX $PM_{2.5}$ concentrations up to ~80 mg/m^3. Similar to the IonZG smoke detector, the STS ion detector had higher sensitivity for smaller particles. The signal became nonlinear at high concentrations (above ~200 mg/m^3) and this detector had low signal-to-noise ratio for concentration $\lesssim$5 mg/m^3.

Figure 6e shows that the ISS scatter detector signal increased approximately linearly with DRX $PM_{2.5}$ concentrations between ~1-15 mg/m^3. The data had a wider spread than other detectors, probably due to the extra plumbing and lack of a pump causing non-uniform concentrations in the sensing zone of this detector. The ISS scatter detector signal increased faster for larger particles than smaller particles as a function of DRX $PM_{2.5}$ concentrations. The signal saturated at ~6 V at higher concentrations.



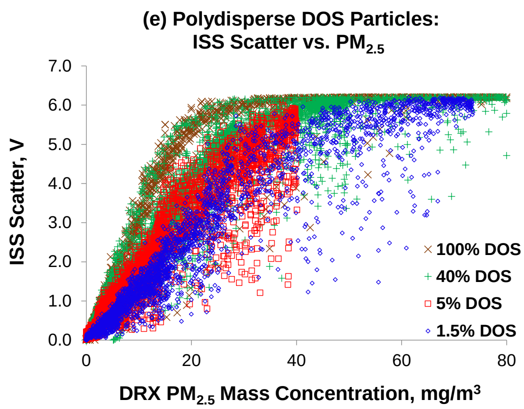


Figure 6. Smoke detector responses as a function of DRX $PM_{2.5}$ concentration for polydisperse DOS particles generated by the TSI 3076 atomizer using four different DOS solution (in isopropyl alcohol) concentrations. Only up to 80 mg/m^3 $PM_{2.5}$ concentrations are shown to more clearly illustrate the 5% DOS case.

C. Smoke Detector Response to Smoke Particles

An example of instrument responses to smoke evolution from smoldering lamp wick is illustrated in Figure 7. All instruments responded to smoke concentrations after the smoke filled the chamber at around 1000 s. The signal of light scattering-based instruments (i.e., DRX, obscuration meter, CSP detector, and ISS scatter detector) increased linearly with smoke concentration, whereas those of ionization-based instruments (i.e., IonZG and STS ion detector) decreased nonlinearly with smoke concentration. The STS ion and ISS scatter detectors saturated at higher concentrations. The light scattering smoke alarm (Kidde P3010H) was triggered earlier and ended later than the ionization smoke alarm (Kidde I12010S).

To evaluate the feasibility of using reference aerosols to predict smoke detectors' responses to combustion aerosols, Figure 8 compares the slopes for CSP detector, obscuration meter, and ISS scatter detector when linearly regressed against the DRX $PM_{2.5}$ concentrations. Because these four measurements are based on light scattering or extinction, signals were linearly correlated with correlation coefficients > 0.95. Mineral oil particles had the lowest slopes among all tests, while the DOS particles from the four solution concentrations covered the slope range for most tested smoke aerosols. The regression slopes between the CSP detector and the DRX had lower variations (COV = 13%) among different aerosols than those for the obscuration meter (COV = 26%) and ISS scatter detector (COV = 35%). While the optical design of the CSP detector is proprietary, its optical measurement is probably similar to that of the DRX, which detects light scattered at an angle range of 90 ± 62° relative to the laser beam.[4] The larger COV for the ISS scatter detector is likely caused by its different optical design from the DRX: it uses a near infrared laser and measures forward light scattering (30°). Furthermore, its signal saturated at lower concentrations.

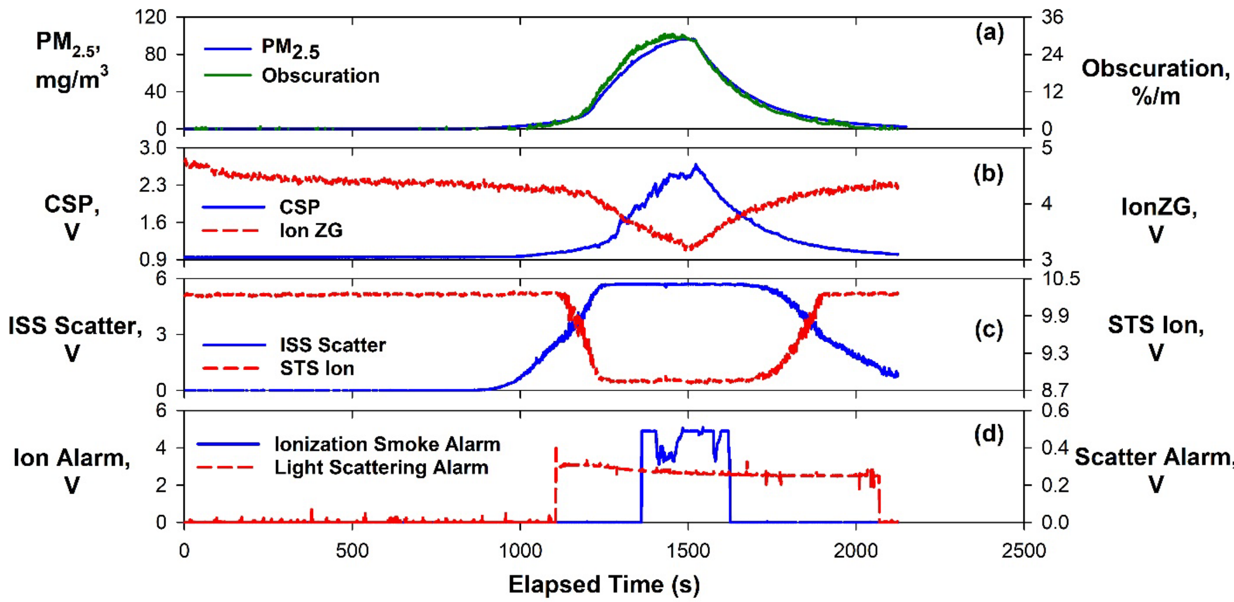


Figure 7. Example time series of instrument responses to the evolution of smoke particles from a smoldering lamp wick test. Around 100 s, one gram of lamp wick was added to the tube furnace which was fast ramped up to 200 °C. All instrument responded to the smoke concentration changes. The fuel boat was taken out around 1500 s and the smoke chamber was purged slowly starting from ~1560 s.

The regression slope ratios (smoke over reference aerosols) for each pair are summarized in Table 1. For the CSP detector (Table 1a), its responses to lamp wick particles were similar to those for 5% or 100% DOS particles; its responses to Kapton and PMMA particles were similar to those for 1.5% or 5% DOS particles; and its responses to wire insulation particles were similar to 5% DOS particles. The CSP detector's response to mineral oil particles were lower than all smoke aerosols except Teflon. Polydisperse DOS particles from 5% solution were able to predict responses of different smoke particles within an error of ±10% except for ~20% overestimation of Teflon smoke. On the other hand, mineral oil reference particles underestimated most smoke particle responses by 20–35%, but with a good representation for Teflon smoke particles.

The obscuration meter had linear response with the DRX over a wide $PM_{2.5}$ concentration range of ~5–200 mg/m^3. However, it had low signal-to-noise ratios for $PM_{2.5}$ concentration ≲5 mg/m^3 (~1%/m obscuration). Therefore, the DRX was used as the reference. As shown in Table 1b, the responses of the obscuration meter to lamp wick smoke could be predicted by 40% or 100% DOS particles; responses to Kapton and Nomex smoke could be predicted by 1.5% DOS; and responses to PMMA and wire insulation smoke could be predicted by 40% and 5% DOS, respectively. Teflon particles generated the highest slope among all tested materials (Figure 8b), and its slope was 16% higher than 100% DOS particles. Mineral oil particles would underestimate the responses of all smoke particles by factors of up to 2.5.

The responses of the ISS scatter detector to smoke aerosols differed from reference aerosols by more than 10% except that PMMA particle signals could be predicted by 5% or 40% DOS particles within 6% error (Table 1c). Within ±20% error, 1.5% DOS particles was able to predict Kapton particles; either 5% or 40% DOS could predict Nomex, PMMA, and wire insulation particles; and 100% DOS could predict lamp wick and Teflon particles. Similar to the CSP detector and obscuration meter, ISS scatter detector responses to smoke particles would be underestimated by a factor of over three if mineral oil particles were used as the reference aerosol.

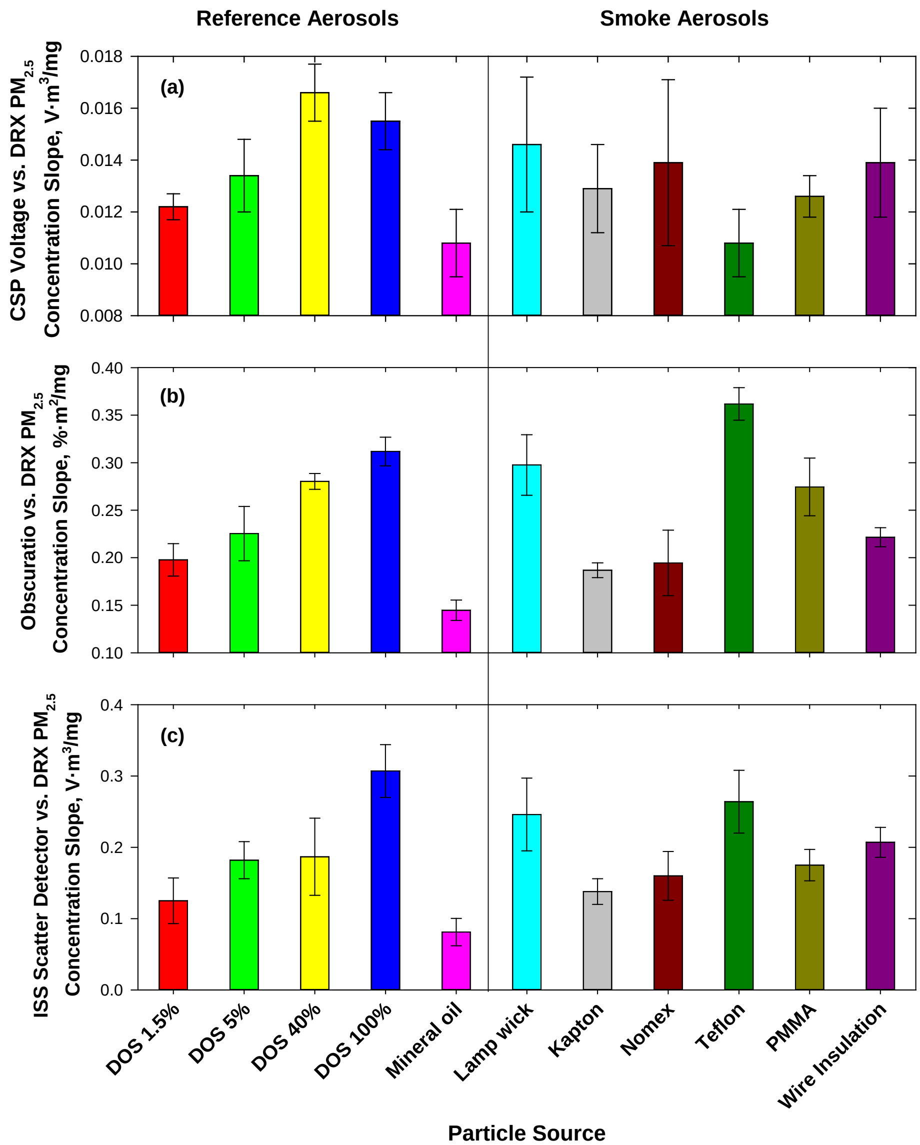


Figure 8. Comparison of linear regression slopes between (a) CSP detector, (b) obscuration meter, and (c) ISS scatter detector (for signals <4 V) and DRX $PM_{2.5}$ concentration for reference and smoke aerosols. The error bars represent the linear regression slope uncertainty (standard deviation).

This study shows that while the 1.5%–100% DOS particles and mineral oil particles covered the response slope range of most smoke particles, there was no single reference aerosol that predicted the responses of the CSP detector, obscuration meter, and ISS scatter detector to different smoke aerosols within ±10% error. The 5% DOS particles predicted smoke aerosol responses within ±20% error for the CSP detector, while mineral oil particles consistently underestimated smoke aerosol responses except for Teflon particles. It is possible to use the slope ratios in Table 1 as conversion factors to predict smoke aerosol responses by reference aerosols. Alternatively, multiple reference aerosols can be used for different smoke detectors and different smoke particles.

Table 1. Linear regression slope ratios of smoke over reference aerosols. Slopes ratios highlighted in green indicate differences within ±10%.

(a) CSP vs. DRX	Lamp Wick	Kapton	Nomex	Teflon	PMMA	Wire Insulation
DOS 1.5%	1.20	1.06	1.14	0.89	1.03	1.14
DOS 5%	1.09	0.96	1.04	0.81	0.94	1.04
DOS 40%	0.88	0.78	0.84	0.65	0.76	0.84
DOS 100%	0.94	0.83	0.90	0.70	0.81	0.90
Mineral Oil	1.35	1.19	1.29	1.00	1.17	1.29

(b) Obscuration vs. DRX	Lamp Wick	Kapton	Nomex	Teflon	PMMA	Wire Insulation
DOS 1.5%	1.51	0.94	0.98	1.83	1.39	1.12
DOS 5%	1.32	0.83	0.86	1.61	1.22	0.98
DOS 40%	1.06	0.67	0.69	1.29	0.98	0.79
DOS 100%	0.95	0.60	0.62	1.16	0.88	0.71
Mineral Oil	2.06	1.29	1.34	2.50	1.90	1.53

(c) ISS Scatter vs. DRX	Lamp Wick	Kapton	Nomex	Teflon	PMMA	Wire Insulation
DOS 1.5%	1.97	1.10	1.28	2.11	1.40	1.66
DOS 5%	1.35	0.76	0.88	1.45	0.96	1.14
DOS 40%	1.32	0.74	0.86	1.41	0.94	1.11
DOS 100%	0.80	0.45	0.52	0.86	0.57	0.67
Mineral Oil	3.03	1.70	1.97	3.26	2.16	2.55

IV. Conclusion

Among the three types of reference aerosols (i.e., mineral oil, DOS, and PSL) tested in this study, polydisperse mineral oil particles generated by the Gemini 501B smoke detector tester and DOS particles generated by the TSI 3076 atomizer were suitable for smoke detector testing. Repeated measurements with mineral oil particles on three different days found that the Gemini 501B smoke detector tester generated polydisperse mineral oil particles with reproducible particle size distributions and that smoke detectors had reproducible responses as a function of the DRX $PM_{2.5}$ concentrations. The TSI 3076 atomizer can vary DOS particle size distributions and concentrations by changing the solution concentration and adjusting a dilution bridge, respectively. Monodisperse DOS particles of 500 nm and 700 nm can be generated with relatively high concentrations, whereas it was a challenge to produce high concentrations of smaller monodisperse particles sufficient for smoke detector testing. It was difficult to produce high concentrations of PSL particles, either by the TSI 3076 or 9306 atomizers.

For both reference aerosols and smoke aerosols generated from smoldering pyrolysis of spacecraft-relevant materials, the responses of smoke detectors based on light scattering or extinction (i.e., CSP detector, obscuration meter, and ISS scatter detector) increased linearly with DRX $PM_{2.5}$ concentrations, whereas responses of ionization smoke detectors (i.e., IonZG and STS ion detector) decreased nonlinearly with DRX $PM_{2.5}$ concentrations. The CSP detector linearity covered a wide range of DRX $PM_{2.5}$ concentrations from <1 mg/m^3 to 200 mg/m^3, depending on aerosol materials. While the CSP detector had high sensitivity at low smoke levels, it only used a narrow voltage range (~0.96 V at baseline and $\lesssim$ 3 V at 30%/m obscuration), which should be increased to improve the signal resolution and reliability.

Using the DRX $PM_{2.5}$ concentrations as the smoke level reference, reference aerosols generated from 1.5%–100% DOS solutions and mineral oil covered the response range of most smoke particles. However, no single reference aerosol can be used to predict all smoke detectors' responses to different smoke aerosols within ±10% error. The 5% DOS particles were able to predict smoke aerosol responses within ±20% error for the CSP detector, whereas mineral oil particles typically underestimated smoke aerosol responses. The relationship between reference and smoke aerosols derived from this study can be used as conversion factors to predict smoke aerosol responses by reference aerosols. Future work should experimentally verify the applicability of the derived conversion factors. Measuring particle size distributions and optical properties of smoke particles, along with light scattering and absorption modeling, will help explain the differences in smoke detectors responses and further guide smoke detector optimization and performance prediction.

Acknowledgments and Disclaimer

This study was supported by Universities Space Research Association (USRA) Contract No. NNC13BA10B, HX5 Contract No. DRIN20D03, and NASA EPSCoR Research CAN Grant No. 80NSSC19M0152. Technical support by and discussions with Mr. Matthew Claassen, Mr. Christopher Pestak, and Dr. David Urban are gratefully appreciated. Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

References

1. UL. "UL 217: Standard for Smoke Alarms." 8th ed., Underwriters Laboratories Inc., Northbrook, IL, 2015.
2. Kulis, M. J., Meyer, M. E., Mudgett, P. D., Berger, G. M., and Pilgrim, J. S. "Heating of Printed Circuit Board, Wire Insulation and Electronic Components for Fire Signature Sensor Evaluation," *44th International Conference on Environmental Systems*. Tucson, Arizona, 2014.
3. ASTM. "ASTM E662-17a, Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials." American Society for Testing Materials International, West Conshohocken, PA, 2017.
4. Wang, X. L., Chancellor, G., Evenstad, J., Farnsworth, J. E., Hase, A., Olson, G. M., Sreenath, A., and Agarwal, J. K. "A Novel Optical Instrument for Estimating Size Segregated Aerosol Mass Concentration in Real Time," *Aerosol Science and Technology* Vol. 43, No. 9, 2009, pp. 939 - 950.
5. Wang, X. L., Zhou, H., Arnott, W. P., Meyer, M. E., Taylor, S., Firouzkouhi, H., Moosmüller, H., Chow, J. C., and Watson, J. G. "Characterization of smoke for spacecraft fire safety," *Journal of Aerosol Science* Vol. 136, 2019, pp. 36-47.
6. Wang, X. L., Zhou, H., Arnott, W. P., Meyer, M. E., Taylor, S., Firouzkouhi, H., Moosmüller, H., Chow, J. C., and Watson, J. G. "Evaluation of Gas and Particle Sensors for Detecting Spacecraft-Relevant Fire Emissions " *Fire Safety Journal* Vol. 113, 2020.
7. Wang, S. C., and Flagan, R. C. "Scanning Electrical Mobility Spectrometer," *Aerosol Science and Technology* Vol. 13, 1990, pp. 230-240.
8. Knutson, E. O., and Whitby, K. T. "Aerosol Classification by Electric Mobility: Apparatus, Theory, and Applications," *Journal of Aerosol Science* Vol. 6, 1975, pp. 443-451.
9. Hering, S. V., Stolzenburg, M. R., Quant, F. R., Oberreit, D. R., and Keady, P. B. "A Laminar-Flow, Water-Based Condensation Particle Counter (WCPC)," *Aerosol Science and Technology* Vol. 39, No. 7, 2005, pp. 659 - 672.
10. Urban, D., Ruff, G., Brooker, J., Cleary, T., Yang, J., Mulholland, G., and Yuan, Z.-G. "Spacecraft Fire Detection: Smoke Properties and Transport in Low-Gravity," *46th AIAA Aerospace Sciences Meeting and Exhibit*. American Institute of Aeronautics and Astronautics, Reno, NV, 2008, pp. 1-9.