"SMOKE:" Characterization of Smoke Particulate for Spacecraft Fire Detection

D.L. Urban[1], G. Mulholland[2], Z.G. Yuan[3], J. Yang[2], T. Cleary[2]
[1]NASA Glenn Research Center, Cleveland OH
[2]National Institute for Standards and Technology, Gaithersburg, MD
[3]National Center for Microgravity Research in Fluids and Combustion, Cleveland, OH

Introduction

"Smoke" is a flight definition investigation whose purpose is to characterize the smoke particulate from microgravity smoke sources to enable improved design of future space-craft smoke detectors. In the earliest missions (Mercury, Gemini and Apollo), the crew quarters were so cramped that it was considered reasonable that the astronauts would rapidly detect any fire. The Skylab module, however, included approximately 30 UV-sensing fire detectors (Friedman, 1992). The Space Shuttle Orbiter has 9 particle-ionization smoke detectors in the mid-deck and flight deck (Martin and DaLee 1993). The detectors for the US segments of the International Space Station (ISS) are laser-diode, forward-scattering, smoke detectors. Current plans for the ISS call for two detectors in the open area of the module, and detectors in racks that have cooling air-flow (McKinnie, 1997). Due to the complete absence of microgravity data, all three of these detector systems were designed based upon 1-g test data and experience. As planned mission durations and complexity increase and the volume of spacecraft increases, the need for and importance of effective, crew-independent, fire detection will grow significantly, necessitating more research into microgravity fire phenomena.

In 1997 the Comparative Soot Diagnostics Experiment (CSD) flew in the Orbiter Middeck as a Glovebox payload (Urban et al, 1997). The CSD experiment was designed to produce small quantities of smoke from several sources to obtain particulate samples and to determine the response of the ISS and Orbiter smoke detectors to these sources. Marked differences in the performance of the detectors compared to their behavior in 1-g were observed. In extreme cases, the detector used in the orbiter was completely blind to easily visible smoke from sources that were readily detected in 1-g. It is hypothesized but as yet unverified that this performance difference was due to enhanced growth of liquid smoke droplets in low-g. These CSD results clearly demonstrate that spacecraft smoke detector design cannot be based on 1-g experience.

Background

Other than the data from CSD, the smoke particulate studied from long-term microgravity sources is limited to soot from gas jet diffusion flames (Urban et al., 1997). Particulate have also been captured from over-heated wire insulations in the drop tower. (Paul et al., 1993 and Srivastava, McKinnon and Todd, 1998) but these data are limited by the short drop durations. Other than CSD, none of these investigations considered liquid droplet smokes. Since many overheated materials in low gravity can be expected to produce liquid droplet smokes, it is essential that the microgravity smoke droplet-size distribution be understood. In general, all of these studies have indicated that the particles are larger in low-gravity than in normal gravity. The results clear support the need for additional low-gravity smoke data.

Current Spacecraft Smoke Detector Designs

Both the ISS and the Orbiter smoke detectors were designed based upon the best data available at the time; nevertheless, their sensitivity to smoke particle size are very different.. The

Brunswick Defense design for the Orbiter consists of a dual-chamber ionization detector that is in the flow path created by a vane pump. Such detectors are most sensitive to high concentrations of small particles. This vane pump provides some active sampling capability and also the flow for an inertial separation system that is designed to make the detector insensitive to particulate larger than 1 to 2 μm , depending upon the particle density. It is a concern that this separator may remove a large fraction of some smokes produced microgravity conditions. The design developed for the ISS by Allied Signal consists of a 2-pass laser diode obscuration system that also has a photo-diode positioned to sense forward scattered light (30 degrees). The system is designed to alarm based on the magnitude of the scattered light signal with dust discrimination based on frequency analysis of the scattered light signal. The system is less sensitive to particles smaller than the wavelength of the laser (near IR) than it is to larger particles. The minimum reported sensitivity is 0.3μm. Thus, it is seen that one detector is most sensitive to small smoke particles smaller than 0.3 μm and the other most sensitive to particle sizes larger than 0.3 μm.

CSD Experiment Results

In the CSD experiment, small samples of spacecraft materials were heated in a small duct that contained a thermophoretic sampler and was connected to the spacecraft smoke detectors. Results from two tests are shown in figures 1 and 2. In figure 1, the smoke detector response for overheated silicone rubber is shown. Low response by the ionization detector in low gravity is evident. In contrast, the results for a solid particle smoke (Kapton*) are shown in figure 2. In this case, both detectors performed well. These results are typical of the results seen for other smoke types. When the thermophoretic probes were returned to earth, the grids were removed and analyzed in a TEM to determine the primary particle and aggregate size distribution. Figure 3 contains TEM images of typical particulate from Teflon*, Kapton* and Candle tests. Table 1 summarizes the results for the tests for which comparable particulate samples were collected for 1-g and low-g. Significantly, despite strong smoke levels visible in the video record, no particulate material was found on the TEM grids for overheated paper and silicone rubber tests. The suspected cause of this is that the particulate for these materials is actually liquid droplets that later evaporated or spread out on the grids' surface, rendering them undetectable by the TEM. In summary, the CSD experiment demonstrated that smoke particulate properties can change with gravity level. The effect seems to be greater for liquid droplet smokes, however this was unverified since the droplet size distribution was not obtained for these smokes.

Material	Low-g Primary Diameter (nm)	1-g Primary Diameter (nm)	Low-g Aggregate Length (nm)	1-g Aggregate Length (nm)
Kapton	76	35	223	N/A
Candle	34	17	976	265
Teflon	136	75	662	277

Table 1 Properties of Smoke Particulate Generated in Reduced Gravity and in Normal Gravity
Shown in each column is the log-normal average diameter (geometric mean diameter).

Objectives of the flight investigation

Given the results of the CSD experiment, it is evident that more data on liquid droplet smoke in microgravity are critically needed. To address this issue, this investigation was proposed with the following four objectives. 1. Improve the reliability of future spacecraft smoke detectors by making measurements of the smoke particulate size distribution that are needed for rational

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design of smoke detectors. 2. Compare the measured effect of μg on the size distribution of liquid aerosol smokes with the predicted effect. 3. Evaluate the performance of the two existing U.S. spacecraft smoke detector designs for the test conditions. 4. Evaluate other smoke detection/sensing devices at NASA's request for the test materials.

Description of the Planned Flight Experiment

The new investigation is based on the design heritage of the CSD experiment but will add new diagnostics to provide on-orbit measurements of critical moments of the smoke size distribution. The planned approach will use commercial particle measurement devices in the new Microgravity Science Glovebox (MSG) planned for ISS. The test samples will be similar to those used previously except more liquid smoke producers will be used and a reference sample will be designed. The added diagnostics will include a commercial condensation nucleus counter to measure the number concentration of the aerosol, the ionization smoke detector to measure a moment involving the particle concentration times the diameter, a commercial light scattering instrument with a signal approximately proportional to the number concentration times the particle volume, a heated thermophoretic sampling probe and potentially a particle classifier based upon MEMS technology. This combination of instruments is sufficient to allow computation of the critical smoke particle size parameters

Modeling of Aerosol Generation

To assist experimental design and to provide an analytical context for interpretation of the results from the reference sample, a numerical model is planned. The model will be used to predict the formation of aerosol (nucleation) and its subsequent growth (via condensation and coagulation). The numerical calculation will be carried out in two parts. The first part is to compute the vapor distribution, temperature distribution, and flow field using direct numerical simulation of the laminar flow. The second part of the calculation is to compute the time evolution of the growing droplets as they traverse through the vapor concentration-temperature field computed in the first part. Preliminary results with the model are shown in figure 4. These predictions were performed using the Fire Dynamics Simulator (McGrattan et al., 2000a, 2000b). The figure indicates that, 10 cm downstream of the source, the μ-g concentration field is circular with a larger peak value than the 1-g case (attributed to the buoyancy induced flow), suggesting that these conditions favor further droplet growth through coalescence.

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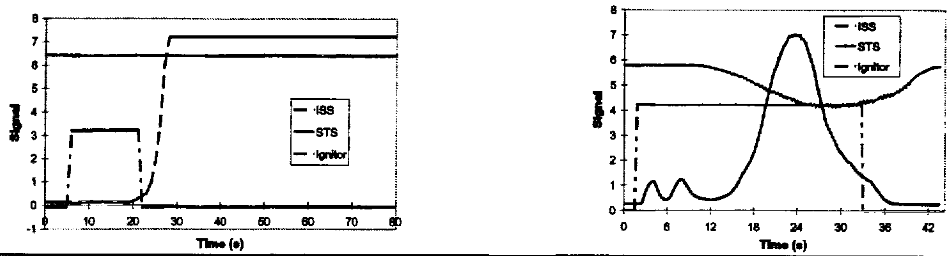

Figure 1: 0-g (left) and 1-g (right) results for silicone rubber. STS detector signal appears as a deviation downward, ISS signal increases with the particulate. The ignitor curve shows the power level. In 0-g the ISS detector saturated while the STS showed no signal. In 1-g both showed good signal.

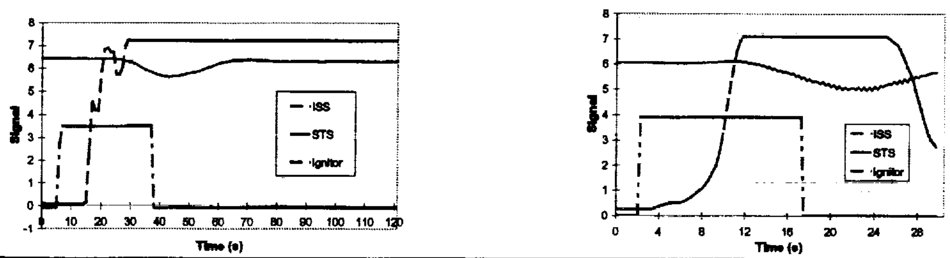

Figure 2: 0-g (left) and 1-g (right) results for Kapton. STS detector signal appears as a deviation downward, The ISS signal increases with the particulate. The igniter curve shows the igniter power level.

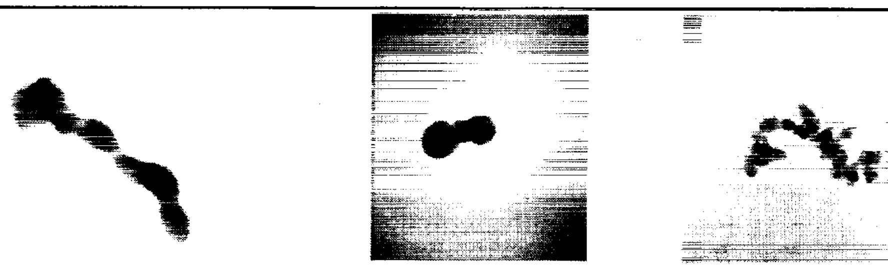

Figure 3: From left to right images of microgravity particulate from overheated Teflon and Kapton and candle soot. Images are at the same magnification

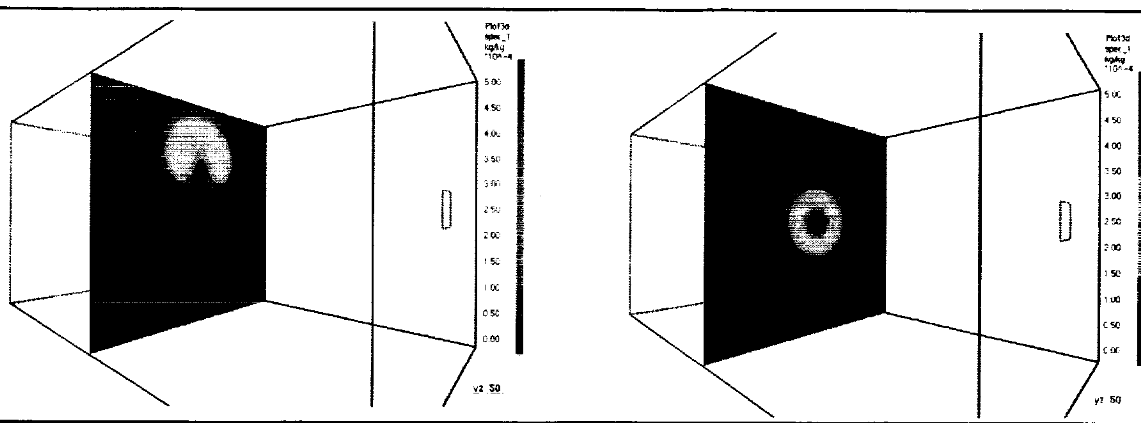

Figure 4: Plots of concentration of vapor 10 cm downstream of the source with a 5 cm/s cross flow. The source is 1 cm x cm and is water vapor at a temperature 50 degrees C above the ambient, (0 degrees C). The flow direction is perpendicular to the direction of gravity. Normal gravity results are on the left and low-gravity on the right.