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Detection of spacecraft fire signatures and post-fire aerosols—Part I: Ground-based results

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ABSTRACT

Preventing fires in spacecraft and other remote platforms is an important facet of avoiding fires that potentially compromise missions, hardware, and crew. If a fire occurs, the objective is to detect the associated fire signatures at the earliest possible time from inception, thus minimizing propagation and collateral damage while providing maximal margin for suppression. The goal is to provide detection sensitivity without introducing spurious false alarms that compromise operations and trigger responsive abatement and containment provisions. A related issue in sealed, self-contained environments is post-fire clean up, and sensors to evaluate the environmental suitability in crewed quarters. In both situations, knowledge of the particulate and/or gaseous fire signatures as they occur under the unique combination of a reduced-gravity environment and materials typical of spaceflight applications is essential for the design of spacecraft fire detectors and habitat sensors. This paper describes recent ground and spaced-based data on fire signatures, and the response of a novel multi-channel optical scattering sensor. This detector, known as the Multi-Parameter Aerosol Scattering Sensor (MPASS), determines multiple moments of the aerosol distributions. The methodology for designing a sensor with the desired response function is discussed, as well as test results that demonstrate the performance of prototype devices.

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1. Introduction

Fire safety is a subject of considerable terrestrial interest, and is a more significant issue in remote enclosed spaces such as aircraft, spacecraft, and submarines. In these situations, the occurrence of fires can jeopardize flight systems, and compromise both mission objectives and crew safety. For these reasons, efforts are conducted under NASA's Fire Prevention Project to address all features relating to spacecraft fire safety. These activities range from the evaluation of materials, fundamentals of ignition and flame spread, reliable early warning detection, methods for suppression, and characterization of the post-fire environment. Numerous features of this project arise from the unique physical aspects of combustion occurring under conditions of reduced gravity.

Descriptions of existing spacecraft fire safety systems are provided in papers by Friedman and Urban [1,2]. The specification of fire detection requirements for the Space Shuttle and International Space Station (ISS) are detailed in Steisslinger et al. [3] The technical detail represented in these requirements is relatively sparse in terms of specifying actual particle size distributions. The Shuttle detector was required to alarm at a concentration of 2 mg/m^3, as tested in response to a monodisperse sample of one micrometer particles. An alternate specification for the same detector requires an alarm when a rise in concentration of 0.022 mg/m^3/s is observed for 20 s. The ISS detection system is required to alarm at a corresponding obscuration of 1%/ft, where this quantity is measured using an Underwriters Laboratory (UL) smoke box and a white light extinction meter. In the actual calibration procedure, a monodosperse aerosol of 0.5 μm polystyrene (PSL) beads was used as a transfer standard, first calibrated against the smoke box/white light meter, and then used to adjust the alarm setpoints for the actual ISS detectors. Given the more recent understanding of both fire detection systems and reduced gravity combustion phenomena, it is notable that these requirements do not encompass the characteristics of the fire signatures themselves. In particular, neither the Shuttle or ISS detectors were calibrated or tested using aerosols produced by relevant spacecraft materials.

While fire or overheat events are uncommon in spacecraft, they have occurred. As such, it is important to understand the chemical and particle hazards that may result, and institute appropriate countermeasures. This situation is similar in many aspects to the exposure of firefighters and emergency responders to chemical and particle aerosols produced by residential, industrial, and wildland fires. Numerous efforts have been conducted to characterize the respiratory hazards associated with such events [4]. The problem is inherently complex and dynamic in nature,

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Nomenclature

$P_{\det}(\theta)$	detected optical power at polar angle θ
$S_{1,2}(\theta,d,n,\lambda)$	mie scattering functions for S and P polarizations, respectively
d	particle diameter
CMD	count median diameter of aerosol size distribution
GSD	geometric standard deviation of aerosol size distribution
d_{SMD}	surface area mean diameter
$d_{\bar{m}}$	diameter of Average Mass
λ	wavelength of incident light
n_p	particle refractive index
$P(d)$	size distribution for particles of diameter d
N	aerosol number concentration
V_{conv}	aerosol volume concentration
P_{in}	incident laser power

factoring in variables such as the basic materials involved, sources of ignition, structural details and ventilation mechanisms. The coupling of these factors causes each situation to spatially and temporally evolve in a unique fashion. For this reason, global exposure values have not yet been formulated for either terrestrial or space applications. Nonetheless, many of the products of fire are known respiratory hazards, and a number of studies have established definitive links between exposure and negative health outcomes [5]. As noted, the situation in spacecraft presents distinct features, in part due to the specialized materials and configurations, but also due to differences in combustion occurring under reduced gravity. The tests described here are a more recent attempt to characterize the products produced by simulated combustion events. Standards for acceptable levels for the primary gaseous species have been established, and are referred to as Spacecraft Maximum Allowable Concentrations, or SMAC values. Analogous levels for particles have not been formally established, with a present default conforming to the ACGIH (American Conference of Governmental Industrial Hygienists) TLV (Threshold Limit Value) of 3 mg/m^3 for PNOS—Particles (insoluble or poorly soluble) Not Otherwise Specified [6]. The effort described here represents initial steps in the development of sensors to further our understanding of these phenomena, and ultimately provide for real-time detection and environmental monitoring.

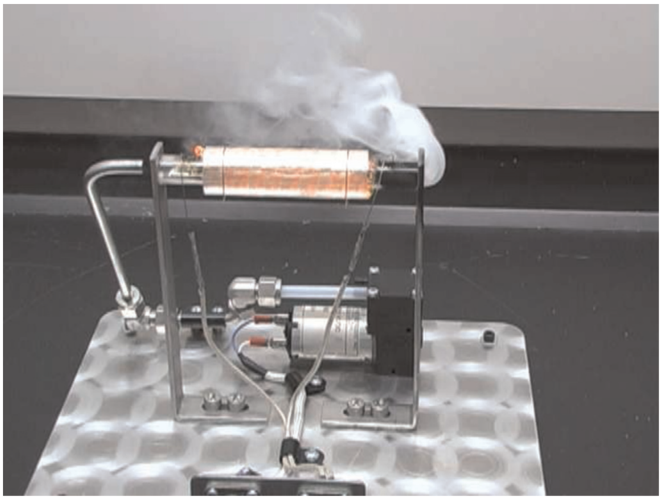

Fig. 1. Sample smoke generator. The sample material is placed in the tube heater. Air from a controlled pump is introduced from the left.

2. Experiment set-up

2.1. Ground-based facility and smoke generator

A series of tests were conducted using a facility developed for this purpose at the NASA White Sands Test Facility (WSTF). This activity also included the evaluation of instrumentation for measuring specific gas-phase chemical components. For details concerning these devices and the related results, the reader is directed to Ruff et al. [7].

The chamber consists of a sealed, instrumented glovebox with a volume of 623 L (22 ft^3), connected to a vent stack to allow the contents to be purged after each run. The chamber is filled with ambient air at 12.4 psia, the ambient atmospheric pressure at WSTF. Two circulating fans are located internally, and are operated continuously during every test. Two removable plates provide access to the interior, and a number of ports are provided for both electrical feedthroughs and gas sampling.

The smoke generator is shown in Fig. 1. The sample is placed at the midpoint of a quartz-lined electrical tube heater. A controllable pump provides a flow of air across the heated sample, driving the aerosol into the volume of the chamber. The flowrate of approximately 1.5 l per minute was constant for all tests. A variety of smoldering conditions were generated by fixing the flowrate and operating the heater at temperature setpoints between 350 and

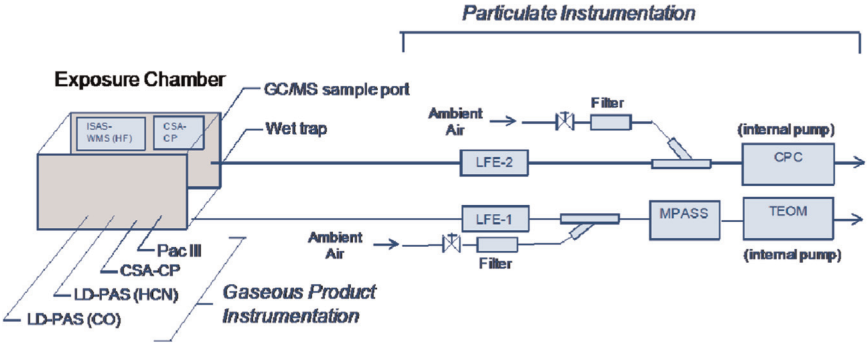

Fig. 2. Schematic of instrumentation used in ground-based testing.