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SMOKE DETECTION IN LOW-G FIRES

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Introduction

Fires in spacecraft are considered a credible risk (Refs. 1-3). To respond to this risk, NASA flew fire detectors on Skylab and the Space Shuttle (STS) and included them in the design for International Space Station Alpha (ISSA). In previous missions (Mercury, Gemini and Apollo), the crew quarters were so cramped that it was not considered credible that the astronauts could fail to observe a fire. The Skylab module included approximately 20 UV fire detectors. The space shuttle has 9 ionization detectors in the mid deck and flight deck and Spacelab has six additional ionization detectors. The planned detectors for ISSA are laser-diode, forward-scattering, smoke or particulate detectors. Current plans for the ISSA call for two detectors in the open area of the module and detectors in racks that have both cooling air flow and electrical power. Due to the complete absence of data concerning the nature of particulate and radiant emission from low-g fires, all three of these detector systems were designed based upon 1-g test data.

As planned mission durations and complexity increase and the volume of spacecraft increases, the need for and importance of effective, crew independent, fire detection grows significantly. This requires more knowledge concerning low-gravity fires and how they might be detected.

To date, no combustion-generated particulate samples have been collected for well-developed microgravity flames. All of the extant data come from drop tower tests and therefore only correspond to the early stages of a fire. The fuel sources were restricted to laminar gas-jet diffusion flames and rapidly overheated wire insulation. These gas-jet drop tower tests indicate, through thermophoretic sampling, (Ref. 4) that soot primaries and aggregates (groups of primary particles) in micro-g may be significantly larger than those in normal-g (n-g). This raises new scientific questions about soot processes as well as practical issues for particulate detection/alarm threshold levels used in on-orbit smoke detectors. Furthermore, it is widely speculated but unverified that the aggregates will grow to very large scales in a microgravity fire of longer duration than available on the ground. Preliminary tests in the 2.2 second drop tower suggest that particulate generated by overheated wire insulation will also be larger in microgravity than in normal gravity (Ref. 5). TEM grids downstream of the fire region in the WIF experiment (Ref. 6) as well as visual observation of long string-like aggregates, further confirm this suggestion. The combined impact of these limited results and theoretical predictions is that direct knowledge of low-g combustion particulate as opposed to extrapolation from 1-g data is needed for a more confident design of smoke detectors for spacecraft.

Background

Although optical detectors (responding to fire's radiant emission rather than particulate emission) were used in the Skylab module and were considered for use on ISSA, their implementation has been hampered by the facts that they require a line-of-sight to the area to be monitored and the lack of knowledge of radiant signatures for low-g fires. Consequently, smoke detection has typically been favored for spacecraft applications and will be the focus of the rest of this paper. Low-g smoke detection has several challenges that make direct application of 1-g technology inappropriate. These issues include: dust discrimination, sampling in the absence of buoyant flows, lack of a knowledge base of low-g fire signatures, lack of knowledge of appropriate alarm levels. Different portions of spacecraft raise unique problems. Inside equipment racks, a likely location for fires given the presence of power and heat-producing devices, free volume is limited and tortuous, however avionics return air may be available (both as an oxidant source and smoke gathering mechanism). Outside the racks, in the crew space, free volume is much less limited and potential ignition sources are less frequent but potential fuel is more common (e.g. paper, clothing, and trash materials). In addition, residence times for the air in the ventilation system are long (tens of minutes in some portions of the shuttles). Future operation plans for the ISSA suggest that modules will have systems powered up but no human occupants present. In situations such as this, adequate fire/smoke detection systems for both the racks and the crew space are needed.

Well-established normal-gravity fires emit small particulate of the size range to which ionization detectors are more sensitive than optical detectors (Ref. 7). Less well-established or smoldering fires will produce larger particulate, owing to the large amount of condensed, unoxidized fuel pyrolysis products and the incomplete soot oxidation. For this type of fire, light scattering/obscuration detectors are more appropriate. However, for materials heated slowly as in the very early stages of some fires, the particulate can be very small, favoring ionization detectors (Ref. 8). This analysis was used by Brunswick Defense in their decision to pursue an ionization detector for the STS.(Fig. 1) The design consists of a dual-chamber ionization detector that is in the flow path created by a vane pump. This vane pump provides some active sampling capability and also provides flow for an inertial separation system which is designed to make the detector insensitive to particulate larger than 1 micron. These advantages are offset by a fairly large power consumption (9 Watts), fan noise, and limited life due to the moving parts. The design developed for ISSA by Allied Signal (Fig 2) consists of a 2 pass laser diode obscuration system that also has a photo-diode positioned to sense forward scattered light (30 degrees) on the return path. The system is designed to alarm based on the magnitude of the scattered light signal. Dust discrimination is based on frequency analysis of the scattered light signal. The system is less sensitive to particles smaller that the wavelength of the laser (near IR) than it is to larger particles but is relatively low power (1.5 W) and has a long operational life.

The performance of these two detectors has been compared in normal gravity (Refs. 9 & 10). Consistent with theory, the ISSA detector alarmed more rapidly in cases where large particles were expected (punk smoke) while for smaller particle size sources (over heated wire) the ISSA detector generally responded last. For punk smoke, despite the difference in the time to alarm, the time to initial response was roughly equivalent for both detectors. The implementation (alarm threshold selection) of both of these systems in microgravity is hampered by the lack of knowledge of their performance against low-gravity combustion generated particulate. To address this problem, an experiment (Comparative Soot Diagnostics (CSD)) is in final development that would take advantage of a Glovebox (GBX) Facility. It will provide the first test of these detectors against low-gravity smoke sources. The design of the experiment was constrained by the GBX power and size constraints; in addition toxicity was a significant constraint since one of the most likely spacecraft smoke sources is overheated wire insulation which usually contains fluorine.

Description of Apparatus

The CSD experimental hardware consists of two modules named the Near-Field Module and Far-Field Module as shown in figure 3. The Near-Field Module will be installed inside the glovebox and will contain the sample and the near field diagnostics. The Far-Field module will be external to the glovebox and will contain two spacecraft smoke detectors, exactly matching the STS detector and the prototype ISSA detector. Products from the near field tests will be transported to the far-field box and subsequently back into the glovebox via teflon hoses. These hoses will enter the glovebox through ports in the airlock door. All of the combustion products will be contained in either the glovebox or the far field module; by the time the experiment terminates, all of the products will have been returned to the glovebox.

A schematic of the Near-Field Module is shown in figure 4. It consists of a small test chamber fitted with a sample carrier that holds the sample being tested. Air is blown into the chamber from the right side by a small fan, and flows past the sample, exiting on the left side where it enters the hose to the Far-Field Module. The sample is ignited or overheated by a resistively heated Kanthal wire. The smoke particulate produced is sampled by a rake of thermophoretic probes. The particulate volume fraction measurements are made using two laser light obscuration systems.

Thermophoretic sampling has been used previously in the drop tower for gas jet diffusion flames and for overheated wires (Refs. 4 & 5). For the overheated wire and silicone rubber tests we expect a weak thermal gradient and consequently will leave the probe in place for a longer time (several seconds) than in the case of the much hotter candle flame where we will leave the probe in for 10 to 20 ms. When the probes are returned to earth, the grids will be removed and analyzed in a TEM to determine the primary particle and aggregate size distribution.

In the Near-Field Module, a custom-built laser-light extinction system will measure the volume fraction of the produced particulate in two locations along the axis of the flame. At each location a low-power laser diode with associated collimating optics is directed through a beam splitter. The intensity of one beam is measured by a photodiode to supply a reference signal and the other beam is expanded to approximately 1 cm in diameter and will pass across the chamber perpendicular to the chamber axis to where the beam is imaged on another photodiode. The particulate scatters and absorbs some of the light (extinction) causing a reduction in the signal from the detector. This signal change will be used with particle size information from the thermophoretic probes to calculate the volume fraction occupied by particulate

The Far Field Module (figure 5) consists of a box containing a duct through which the smoke-containing air from the Near Field Module is drawn by a fan. The two spacecraft smoke detectors are attached to the duct and monitor the smoke in the air that passes through it. It is important to note that the detectors are very sensitive and consequently, the tests are designed to generate a very small amount of smoke particulate. It is anticipated that for some of these tests, no visible smoke will be produced, however it should be detectable by all of the near and far-field diagnostics. The signals from the near field extinction photodiodes, sample temperature thermocouple and the two far field smoke detectors will be displayed on digital readouts on the Far Field Module. These readouts will update at 1 Hz and are to be are recorded by a glovebox video camera for subsequent analysis.

Tests have been conducted with the engineering version of the hardware both in 1-g and on the Lear Jet and the KC-135. These tests were designed to allow determination of the correct sample size and heater geometry to produce acceptable signal levels at the detectors and to keep the total particulate emission low enough that there are no safety concerns. To achieve detectable particulate at the detectors in the Far Field Module, mass losses of approximately 2 mg are needed. The samples are designed so that repeatable mass losses can be achieved at different heating rates by varying the amount of igniter wire in contact with the sample and the temperature and activation time of the ignitor. Typical conditions are 60 seconds activation time with an approximately 350 C igniter wire temperature for slow heating rate cases and 15 to 30 seconds activation time with an approximately 500 C igniter for the high heating rate cases.

These conditions will be refined in the future when the flow duct in the engineering hardware is updated to match the flight hardware.

The first detector in the Far Field Module will be the ISSA prototype duct smoke detector designed by Allied Signal, the second detector is the STS smoke detector designed by Brunswick Defense.

Flight Execution

After installing the near field hardware in the glovebox and attaching the far field module to the glovebox, the operator runs the self diagnostic procedures on the two smoke detectors and activates the GBX video camera, turns on the ignitor for a defined period of time and initiates the thermophoretic soot samplers when the flame is well developed. The actual duration of the combustion event will be of the order of five minutes or less. After the experiment, the operator will stow and reload the soot samplers, the test sample, and the filters at the end of the return line from the Far Field Module. At this point the operator either stows the modules or initiates another run.

Test Matrix

The exact flow and power levels will be determined based on ground based testing with the engineering version of the flight hardware. However, the tests will consist of testing a coflow ventilated candle at three coflow velocities and overheating four materials, (paper, silicone rubber, and teflon and kapton coated wires) at three heating rates. Candles were selected because their particulate will be primarily soot and varying the flow velocity should influence the soot production level and the soot residence time in the flame. Varying the heating rate for the other materials will affect the particle size distribution. The silicone rubber was selected because it is a particle-generation technique developed for testing the STS smoke detectors. While this technique produces almost no visible smoke, its particle generation was studied in 1-g by Brunswick Defense. The wire insulations are from spaceflight rated wire (TFE and Kapton) and were selected because overheated wires are the most credible fire risk on space craft and detection of their smoke emission is an important concern. Paper was selected for the last sample because paper is ubiquitous on spacecraft, the paper being tested is used in flight data files.

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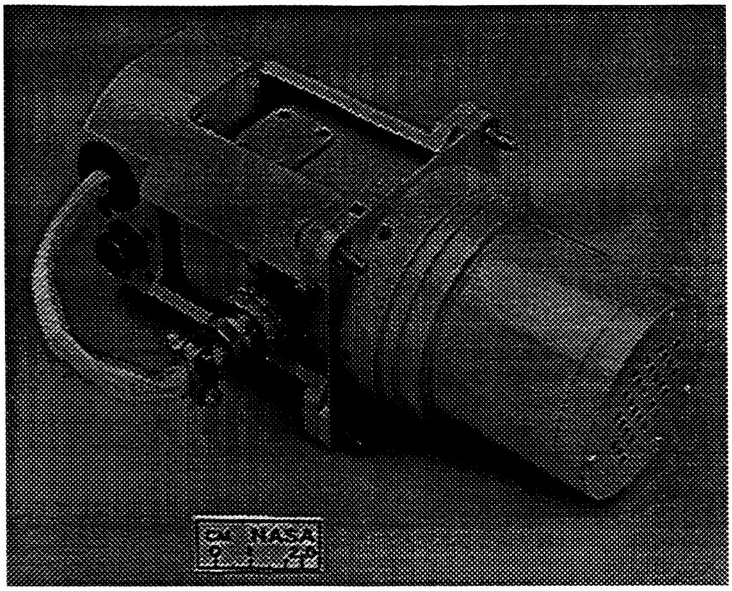

Figure1: Space Shuttle (STS) Smoke Detector (Brunswick Defense). Inlet is on right and outlet from pump is behind small plate on top left.

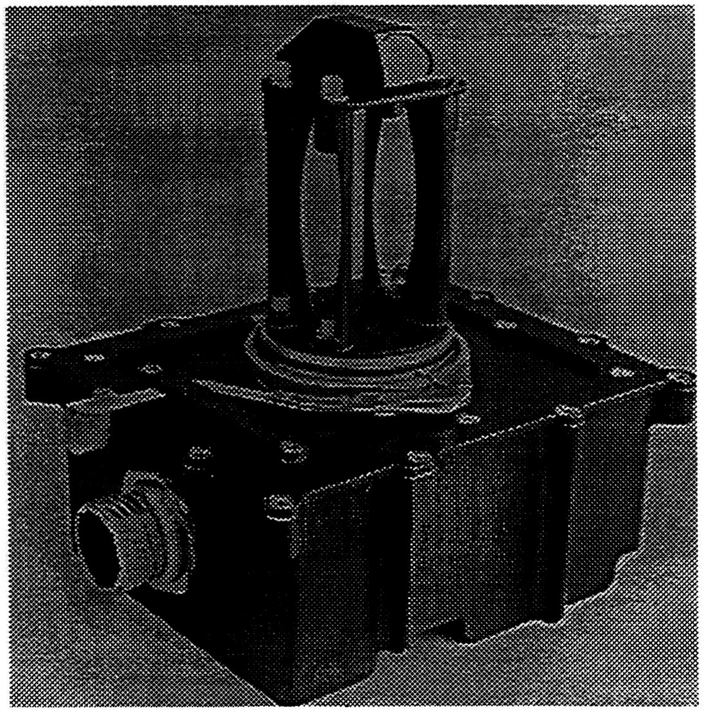

Figure 2: International Space Station Alpha (ISSA) Prototype Smoke Detector (Allied Signal). Laser beam path originates in base reflects off two mirrors on top and returns to the base. The back of one of the mirrors is visible on the top.

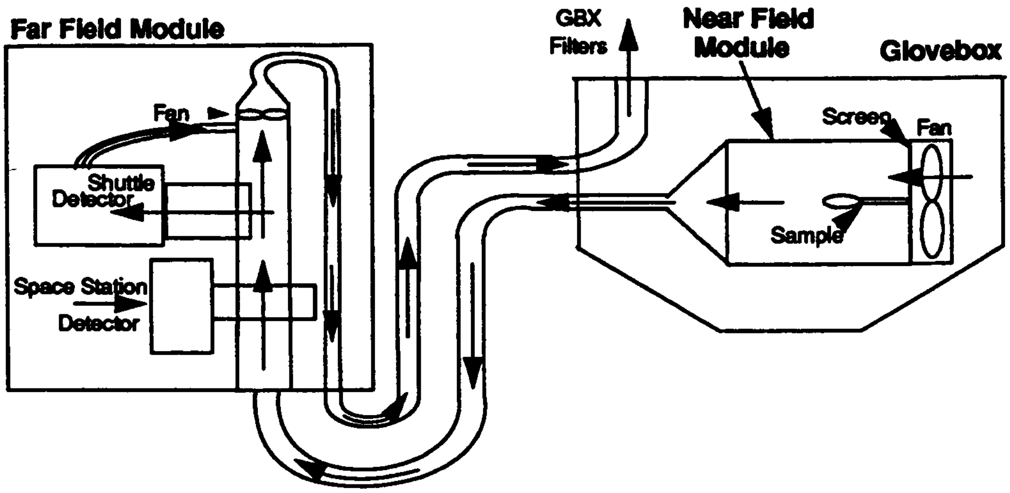

Figure 3: CSD System Schematic

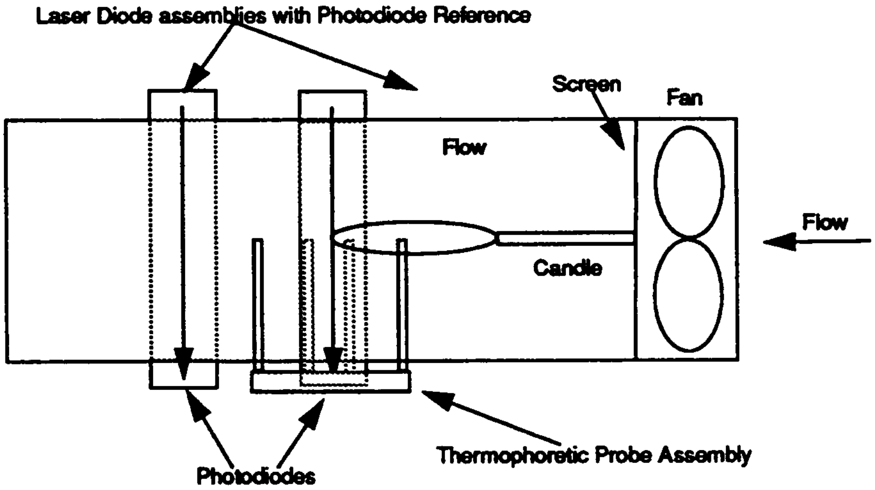

Figure 4: Near Field Module Schematic

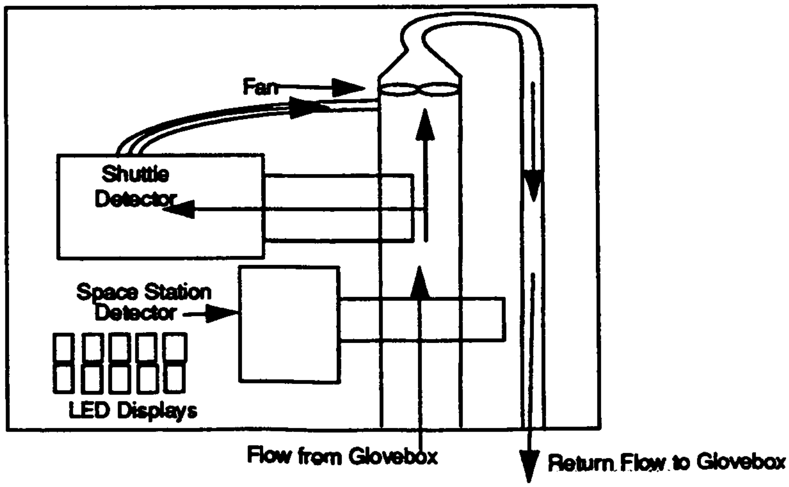

Figure 5: Far Field Module Schematic