Experimental Needs for Spacecraft Risk Assessment

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ABSTRACT

Due to the closed environment of a spacecraft and the lack of egress, fire on-board may pose a significant risk. There are many differences between a fire on-board the spacecraft and one in a terrestrial facility that must be accounted for in any risk assessment. Both the risk assessment methodology and the phenomena-based models for terrestrial applications must be modified. This paper discusses some of the methodology modifications, as well as several experimental results. Multiple experiments have been conducted in terrestrial and microgravity environments in order to construct and validate models required for the assessment and management of risk on-board spacecraft. Past Shuttle experience with electrical overheating events supports the belief that these types of events may pose a serious threat to any human-crewed spacecraft and/or the crew. Experiments have been performed to simulate these events and quantify several damage modes. A preliminary set of experiments at the 2.2 second NASA Lewis Drop Tower has led to several conclusions. First, the production of damage causing elements depends on temperature. Second, the wire insulation involved can have a significant impact on the risk of the event. Third, the smoke particle size distribution is shifted towards larger sizes in microgravity, which may prove important in designing a smoke detector or selecting a sensitivity.

KEY WORDS: risk assessment, methodology, terrestrial, microgravity, experiments.

1.0 INTRODUCTION

Fire on board a human-crewed spacecraft is the threat with potentially the most catastrophic consequences [1,2]. Fire not only threatens the occupants with the obvious dangers of heat, toxic gases, and structural failure, but may also threaten the crew in other, more subtle ways. Both combustion by-products and extinguishing agents can contaminate the atmosphere and/or electrical equipment. In addition, repeated false alarms due to oversensitive detectors can reduce a crew's effectiveness due to relaxation tendencies.

The possibility of having materials that have not been approved for use aboard the spacecraft cannot be realistically eliminated. Furthermore, since an atmospheric environment that supports life must be maintained and electrical equipment may act as ignition sources, it is evident that the fire triangle cannot be completely controlled. Realizing that fire threats exist, designers may use the tool of Probabilistic Risk or Safety Assessment (PRA or PSA) to identify risk management strategies that reduce risk to an acceptable level. The occurrence of major accidents (e.g., Bhopal, Chernobyl, Challenger) has focused the attention of the public on the safety of these facilities. These accidents are rare and any decision-making process that involves them must include the large uncertainties that are associated with their occurrence.

PRA is a methodology that has been designed to deal with rare accidents. It essentially consists of two steps:

1. The identification of scenarios (event sequences) that lead to the consequence of interest, e.g., the release of hazardous materials, crew injuries; and
2. The quantification of the uncertainty associated with the occurrence of these scenarios.

For terrestrial applications of PRA, reasonable models exist to allow the development of accident scenarios that are initiated by fires (Step 1). This is not the case with spacecraft applications because the lack of gravity invalidates the available models for fire growth and suppression. Therefore, the issue that one must face is that of model uncertainty. The quantification of uncertainties (Step 2) is a task that must be put aside until experiments and analysis assure us that the models are reasonable [3].

The state of the art in microgravity combustion research has been reviewed in several workshops [4,5]. Low-gravity research work in the USA, Japan, and Europe has largely focused on fundamental fire science rather than on safety-related aspects [6]. Limited data on flame spread have been produced from ground-based studies with short-term low-gravity exposures (2 to 30 seconds) [7], augmented by a few simple, space-based experiments [8,9]. These tests, usually performed with readily flammable materials, cannot be applied to useful PRA models at this time. Experiments are needed to advance the state of the art by providing information on real scenarios. They will help establish the models that can be used in a PRA analysis, which will be an important step in developing a risk assessment methodology for spacecraft. The need of such a methodology is increasingly being recognized [2].

The subject of this paper is to define experiments to support the development of applicable models and a fire risk PRA data base for human-crewed spacecraft, and to discuss preliminary experiments that have already been conducted. Section 2 discusses the fire risk methodology and the necessary modifications due to the unique impact of a spacecraft environment. Section 3 describes the experiments that have been conducted at the NASA Lewis microgravity facilities while Section 4 offers concluding remarks.

2.0 SPACECRAFT FIRE RISK ASSESSMENT

A probabilistic approach to risk assessment has previously shown success in the safety enhancement of complicated terrestrial systems. A prime example is the use of PRA in nuclear power plants. There are several important differences between a ground-based approach and a human-crewed spacecraft approach. One difference is the definition of the target. In nuclear power plants, for example, the primary targets are cable trays that control or supply power to redundant safety components. In a spacecraft, however, the crew become the primary concern, so they become the primary target. Naturally, areas in the spacecraft that are critical to its operation are also targets, similarly to power plants. A second difference is that, in nuclear power plants, the growth time is defined as the time required for the fire to propagate and damage the cable trays. In a spacecraft application, some events may be transient, and although they may never grow to the point where spacecraft components are threatened, they may, however, produce enough toxins to endanger the crew. Additionally, considering the crew's lack of egress makes the fire scenario more complicated than a single mode to damage, such as heat. This is because the risk of astronaut injury due to an unwanted combustion event cannot be determined as easily as damage to a cable tray. There are other damage modes to consider.

On-board a spacecraft, there are many different fire scenarios that can cause damage to personnel or equipment ranging from insignificant to loss of ship or mission compromise. To find the total risk due to fire, it is necessary to sum the contribution from each scenario as done for nuclear power plant applications. The release of heat, smoke, toxins and corrosives (the four modes to damage for spacecraft) must be considered [10]. It is not unusual to associate heat release with fire. Normally, damage to a critical component is modeled as a function of temperature. Recent studies of damage models have also shown that smoke can be both highly toxic and corrosive. Smoke cannot be ignored, and, in fact, may be more damaging than heat [11]. Toxic substances may also be produced. In space environments, simply opening a door or evacuating the premises is not an option, therefore, the toxin threat becomes more significant in a space environment than it would be on earth.

A unique control and damage time corresponding to each damage mode exists. This forces the control and damage times to depend on the same fire event. In previous PRAs, the control hazard time was assigned a distribution that was developed from statistical evidence and engineering judgement and was independent of the fire's physics [12], such as the actual amount of smoke produced. With this new approach for human-crewed spacecraft, both the control and damage time depend on the same fire event.

In order to analyze the complex behavior associated with the four damage modes, it has been found helpful to distinguish three phenomenological processes. The first is the source or production of the damage-causing species, the second is the transport of the species and the third identifies the deposition and/or attenuation process. This process terminology can be applied to all four damage modes interchangeably. For instance, to describe the smoke and how it affects the scenario, it is necessary to know how much is produced and its characteristics (the source), how the smoke ages and moves to a target (transport), and, finally, how the smoke affects the target, be it a smoke detector, a person or a piece of electronic equipment. In general, models for concentration of the four damage-causing elements as a function of space and time are required. The goal is to relate the concentration of a substance to the physical geometry, environment, and magnitude of the initial wire overload. Models that have been developed for terrestrial applications are invalid due to the lack of buoyancy effects, which dominates combustion processes on earth. Therefore, codes such as COMPBRN [13] are not applicable, since they rely on concepts that become invalid in low gravity environments.

Expected Events and Critical Locations. There have been five electrical overheating events in the Shuttle that tend to support the belief that electrical overheating events may contribute significantly to the fire risk in any human-crewed spacecraft. Obviously, there are electrical components just about everywhere on-board a spacecraft, so both engineering judgement and analysis will play an important role in evaluating which areas would be more likely to have such an event to occur [14]. Due to size and weight constraints, redundancy may be non-existent, so the term "critical location" must have a different definition than for nuclear power plants.

In the Space Station, most fire scenarios that have been examined [15] could be based on incidents originating within a closed compartment termed a "rack," which is essentially a wall drawer [16]. The occupied Space Station volumes, or modules, will be constructed of banks of racks surrounding the central core volume on four sides. Most of the racks will contain electrical equipment; many may also contain flammable solids or fluids. Most importantly, these racks will frequently come into human contact as payloads or scientific experiments are exchanged on a regular basis. Any human contact to the electrical wiring in the rack will increase the probability of an event: wires may become "nicked," mechanically stressed (by bending, pulling, twisting or stripping) to the point where the insulation splits, or an error in re-wiring occurs. It is judged that these areas must be deemed as "critical."

3.0 EXPERIMENTS AND RESULTS

A series of experiments was performed at the NASA Lewis Research Center drop tower to study the behavior of overheating wires in a microgravity environment. The drop tower allows for testing in surroundings nearly absent of gravitational forces, thereby simulating a spacecraft environment.

To generate a reliable estimate of the threat to mission safety from overheated wiring, the sources of possible hazards must be quantified. These potential hazards, as discussed above, include heat, smoke, toxins and corrosives. To effectively model the generation of each of these damage-causing elements, a reliable prediction of the thermal response of a wire to excessive current flow is needed. A microgravity environment provides a unique thermal environment due to the lack of buoyancy induced flows.

The production of each damage-causing element depends on temperature. The generation of smoke is reported to depend upon the temperature of the reaction [17]. Therefore an accurate model that predicts the rate of smoke generation must account for this temperature dependence. The smoke particle morphology is also affected by the unique microgravity thermal environment [18]. The present wiring design for spacecraft implements extensive use of fluoropolymer wire insulations. These fluoropolymers include polytetrafluoroethylene and ethylene-tetrafluoroethylene, commonly known as Teflon and

Tefzel, respectively. These insulations have beneficial mechanical properties and are relatively non-flammable. However, the products of thermal degradation not only pose a serious health risk to the crew, but are also very corrosive and may adversely effect the operation of critical components if deposited upon [19]. The generation of the gaseous degradation products are dependent upon temperature.

The approach of the microgravity experiments discussed in this paper is to overheat insulated wires, representative of those used in spacecraft. The tests consist of exploring the effects of excessive electrical current flow in short lengths of 20 AWG wire. The wire samples are fluoropolymer insulated wires with stranded nickel-coated copper conductors. The ohmic heating created by this current initiates thermal degradation of the wire insulation.

3.1 APPARATUS

The microgravity environment is obtained by use of the NASA Lewis Research Center 2.2-second Drop Tower in Cleveland, Ohio. This facility takes advantage of the fact that while an object is in free-fall, it is not effected by any forces, including a gravitational force. The wire insulation flammability apparatus is assembled in a rigid frame, which is a standard design used in the tower [20]. This frame protects the experiment and the instrumentation. The frame, in turn, is contained inside a metal box that serves as a drag shield. Prior to the test drop, the drag shield and frame package are secured at the top of the tower by a steel piano wire. A piston-driven blade notches the wire, which subsequently fails, releasing the drop package for the 24 meter fall. The experiment frame floats freely within the drag shield during the drop, isolated from external forces (including air drag). The gravitational effect is no greater than 10^{-5} g, where g is the sea-level acceleration of gravity, 9.8 m/s^2. The drop package is decelerated at the bottom of the drop tower by falling into an aerated sand pit, with the majority of the force absorbed by metal prongs extending below the drag shield. The entire apparatus is then retrieved for analysis, reconfigured, and reused.

The experiment set up includes a combustion chamber which is a 20 cm plexiglass cube. The wire is connected between two ignition posts. A solenoid switch with heavy duty contacts is used to close the ignition circuit in which a battery pack supplies the power. The ignition circuit is closed upon the release of the rig from the top of the tower. There is no preheating of the sample in order to prevent any residual convection during the test. The circuit is opened just before impact. Sometimes the sample conductor melts down before the rig impacts, thus opening the circuit and preventing further heating.

The battery pack is capable of producing approximately three levels of power within the wire sample (100, 600, 1200 W). There is some variability depending on the charge of the batteries and, if extra wire is added to the ignition circuit, to increase the resistance. The 600 and 1200 W settings are required for the microgravity tests, so that appreciable combustion can be observed within the short time limit of 2.2 seconds. The 100 W setting is used for long-duration terrestrial tests.

The data are collected with a digital computer called a Tattletale. This computer also provides all the switching capabilities needed by the apparatus. Signal conditioning is achieved with OMEGA OM-5 modules.

The current and voltage drop across the wire sample were measured. These data were used to calculate the volumetric (ohmic) heating rate and determine the wire temperature. The insulation mass loss was determined by weighing the wire sample before and after each test. The smoke production rate was measured using laser obscuration methods in which the laser light is directed through the smoke volume. The attenuated light intensity is compared to the light intensity at the laser source to assess the smoke volume fraction. The smoke particulate diameter distribution was measured using Transmission Electron Microscope (TEM) grids, a method frequently used to sample soot in gas jet flames. When the grid is placed in the smoke, thermophoretic forces move the particulates toward the wafer-thin grid, where they subsequently stick. The grid is then analyzed using a transmission electron microscope to reveal the size and morphology of the particulate matter.

3.2 GENERAL OBSERVATIONS

Once ohmic heating causes insulation degradation, the product gases are enclosed within the annular region between the conductor and the insulation of the wire, causing a pressure increase. In the first series of drop-tower tests (September 1992), substantial gas flow escaped from the ends of the wire. Movement of the wire caused by thermal expansion tended to loosen the insulation and created an avenue for the release of the product gases. In the second series of tests (December 1992), a sample holder limited the wire movement to planar displacement and the axial gas flow was significantly decreased. In a real wiring application, where the wire may be significantly longer, this effect of axial product flow should be lessened. The axial temperature profile would be more uniform due to negligible axial conduction and product gas flow.

Once the insulation reaches a pyrolysis temperature at its external surface or the internal pressure becomes excessive, the wire insulation fails. The video record shows that this insulation breaching is accompanied by a fairly violent expulsion of product gases. It should be noted that the insulation is usually breached before the conductor melts.

Because the wire conductor is actually a helical strand of thinner conductors, some individual strands melt first and may emit molten copper droplets. This phenomenon was observed in several of the high heating-rate tests. These droplets may serve as an additional fire initiator (some droplets were found to be melted into the chamber floor).

The two types of insulation, Teflon and Tefzel, displayed very different burning characteristics. The Teflon had a tendency to melt through on one side and subsequently slough off of the conductor. The Tefzel, on the other hand, would generally remain intact on the conductor and thus more extensive pyrolysis was possible. Another interesting observation was that the smallest nick in the conductor increased the local heat generation, causing the Teflon wire to fail at that point. The Tefzel wire was less sensitive to abrasion. This is a consequence of the different conductor materials, but it could have an impact on the risk assessment due to the fact that the resultant local hot spot could lead to a wire failure more quickly.

3.3 THERMAL RESPONSE

The hot wire poses a thermal threat to nearby components and other wiring. As a result, it is necessary to know the thermal response of the wire during an overload. Additionally, the mass loss and the production of smoke and toxic gases are to be modeled as functions of temperature. The thermal response of the wire conductor includes the ohmic heat generation rate and temperature as a function of time.

The voltage across and the current through the wire sample were simultaneously measured. The rate of ohmic heat generation, $\dot{Q}$, within the wire conductor is then found by the product of the sample voltage, V, and current, I.

$$\dot{Q} = I^2R = IV \quad [W] \tag{1}$$

The heat generation promotes pyrolysis of the insulation. The point at which the conductor fails is important, because the effective temperature of the wire conductor can be related to a specific resistivity value. The melting temperature of the conductor is known to be 1083°C. Given the reference wire resistivity and the resistivity temperature coefficient, the effective conductor temperature can be calculated. The results of these calculations for two different heating rates, 600 W and 1200 W, are shown in Fig. 1. The tests with 1200 W heating rates all resulted in conductor failure (melting). The wire conductor in 600 W tests survived the test duration. For further discussion see Reference [21].

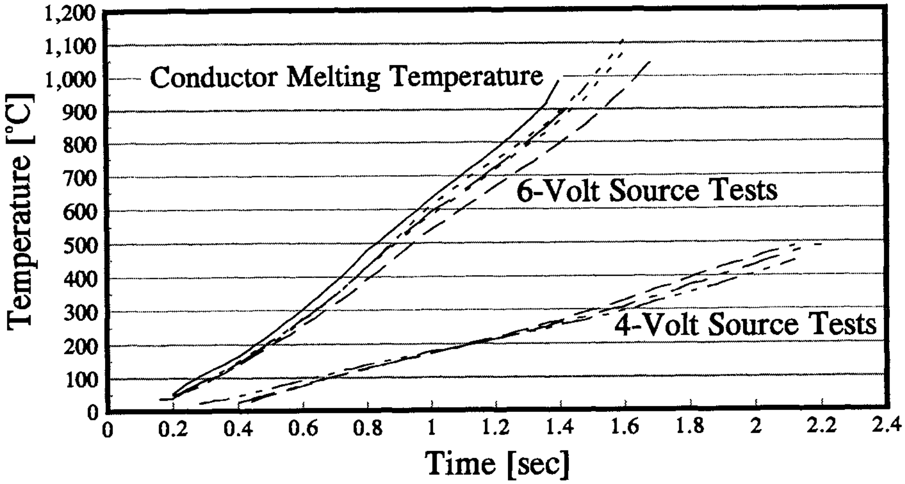

FIGURE 1: Calculated Effective Conductor Temperature at Different Heating Rates

3.4 MASS CONSUMPTION

In order to quantify the amount of smoke and gases evolved during the tests, the wire sample mass is measured before and after each test. Data collected from 1200 W tests have shown a mean value of 31.54% insulation mass loss with a standard deviation of 5.12% for both Teflon and Tefzel. The mean value and small standard deviation illustrate the high data repeatability. Test data from 600 W tests do not agree as well. It is believed that this is simply due to the limited number of 600 W tests and due to the limited test duration (2.2 sec) which does not allow for complete consumption of the wire insulation.

3.5 SMOKE PARTICULATES

An analysis of particulate matter produced by degrading wire insulations provides essential information needed for an eventual comprehensive risk assessment. Not only can this analysis identify and characterize the smoke hazards from a wire-overheating scenario, but it can also establish fire signatures for sensitivity and time-response of smoke detection systems. Estimating the time to detection of a scenario is critical in assessing the damage potential of the four threats.

There is a distinct particle size difference in the terrestrial and microgravity environments. Approximately seventy-five particles were measured for both gravity levels. For spherical particles the diameter was measured, whereas for the ellipsoids the major axis was used. In normal gravity the mean diameter is 151 nm and in microgravity the mean diameter is 330 nm. The particle size also varies over a much greater range in microgravity than in normal gravity. In low gravity conditions, the standard deviation of the particle diameters is 203 nm as opposed to 56 nm in normal gravity.

These particle sizes exhibit a lognormal distribution. The data for both microgravity and terrestrial conditions were curve fitted and are shown in Fig. 2. The major concern here is to determine the reason for such a distinct size difference in an "instantaneous" time period. Presently, the physical mechanisms that cause the differences have not been conclusively determined but the phenomena will be further pursued in future investigations. In addition, the size range exhibited by the particles, for both gravity levels, present problems

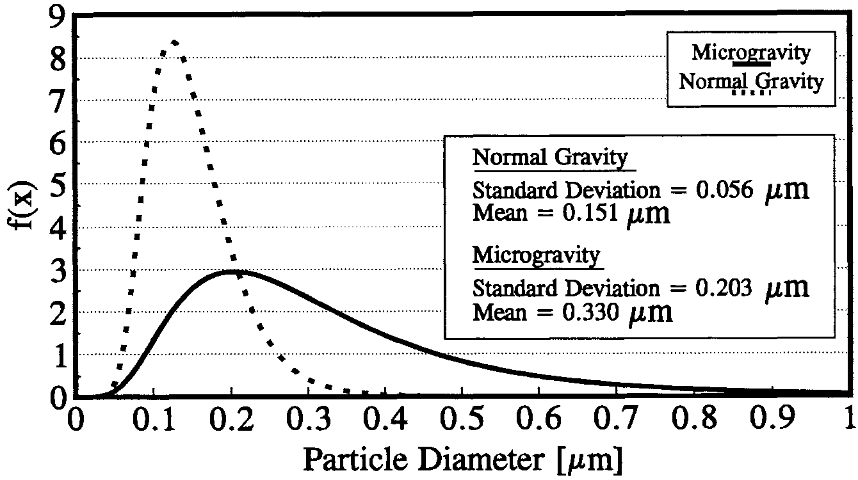

FIGURE 2: Particle Size Distributions

concerning subsequent transport modelling. The particle transport exhibited by this size range is not clearly dominated by either diffusion or inertial effects.

3.6 SMOKE AND GAS PRODUCTION

The production of smoke and toxic gases from the burned insulation may play a significant role in the determination of risk aboard spacecraft. Spacecraft are closed, isolated systems; whatever is put into the air must be removed or the astronauts will inhale it. Thus, the production of smoke and toxic compounds could be a serious threat. There is also the threat to components due to the deposition of corrosive compounds from the gas phase. This may have a long characteristic time, but if the original incident is not detected early enough, then corrosion could be a problem in the future.

Figures 3 and 4 show the smoke mass and smoke fraction as functions of the average heating rate for Tefzel and Teflon, respectively for both normal and microgravity environments. The smoke fraction is the ratio of the smoke mass to the mass of consumed insulation. The tests at high heating rates and higher temperatures are very short (2 seconds), because the conductor melts down, thus ending the test. The lower heating rate tests, conducted under normal gravity conditions, last 10 to 60 seconds. These are all averaged values, because the exact temperature dependence cannot be discerned at this time. However, the total smoke production data do indicate some form of thermal dependence. A balance of masses indicates that, if more smoke is given off per unit of insulation consumed, then there will be less toxic gases produced per unit of insulation consumed, and vise versa.

The fact that Teflon produces less smoke than Tefzel may seem beneficial for fire safety, but not necessarily. The calculation of damage frequency is based on a competition in time between the detection/suppression system and the damage causing elements. A

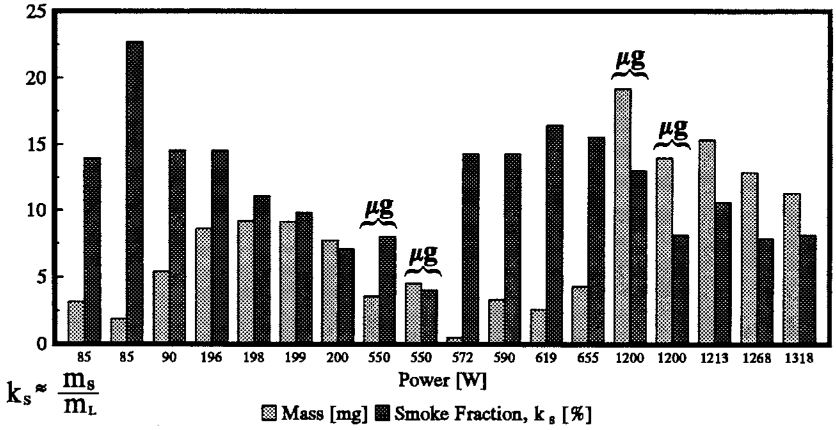

FIGURE 3: Tefzel Smoke Production

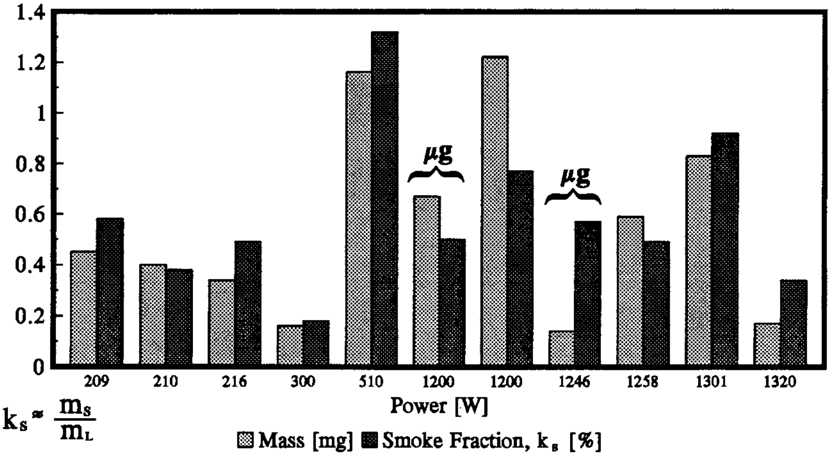

FIGURE 4: Teflon Smoke Production

smaller amount of smoke will increase the time to damage from smoke, however, the detection time will also be increased. If the wire produces more smoke, the event will be detected sooner (and the amount of toxic gases is reduced), thus the possibility of damage may be mitigated. It is unclear what the optimal wire insulation is. The wire insulation selection should be based on actual risk, not just the notion that less smoke is better.

4.0 CONCLUDING REMARKS

Fire is a recognized threat to a wide variety of systems. To perform a fire PRA analysis, models are needed that accurately describe the sequence of events. These models are practically non-existent presently for human-crewed spacecraft applications. Terrestrial-based PRA methodology must be modified to reflect the differences required by a physically isolated system in space. Previous experience and engineering analysis has led to the conclusion that wire overload events pose a significant threat to human-crewed spacecraft.

The production of smoke and toxins are functions of temperature. By monitoring the voltage and current levels, the heat generation rate and the effective conductor temperature were calculated. The amount, size and morphology of the smoke particulates is critical for estimating detection times. Particles were found to be approximately twice as large in microgravity than in normal gravity. The amount of smoke produced from Teflon was considerably less compared to Tefzel. This is beneficial from the point of damage due to smoke, but detrimental for smoke detection and damage due to toxins or corrosives.

Finally, although these experiments are considered to be successful, they only represent a fraction of the possible wire overload currents. More testing using aircraft or space-based platforms with longer durations is necessary in order to study lower heating rates.

Once the phenomenological models are developed for all cases of wire overloads, it will be possible to use PRA methodology to quantify the risk due to wire hazards.

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