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Risks and Issues in Fire Safety on the Space Station

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RISKS AND ISSUES IN FIRE SAFETY ON THE SPACE STATION

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INTRODUCTION

A fire in the inhabited portion of a spacecraft is a greatly feared hazard, but fire protection in space operations is complicated by two factors. First, the spacecraft cabin is an enclosed volume, which limits the resources for fire fighting and the options for crew escape. Second, an orbiting spacecraft experiences a balance of forces, creating a near-zero-gravity (microgravity) environment that profoundly affects the characteristics of fire initiation, spread, and suppression.

The current Shuttle Orbiter is protected by a fire-detection and suppression system whose requirements are derived of necessity from accepted terrestrial and aircraft standards.[1] While experience has shown that Shuttle fire safety is adequate, designers recognize that improved systems to respond specifically to microgravity fire characteristics are highly desirable. Innovative technology is particularly advisable for the Space Station, a forthcoming space community with a complex configuration and long-duration orbital missions, in which the effectiveness of current fire-protection systems is unpredictable.

This paper briefly reviews the development of risk assessments to evaluate the probabilities and consequences of fire incidents in spacecraft. It further discusses the important unresolved issues and needs for improved fire safety in the Space Station, including those of material selection, spacecraft atmospheres, fire detection, fire suppression, and post-fire restoration.

RISK ASSESSMENTS FOR SPACECRAFT

Historical Development

Space systems are traditionally associated with the qualities of high reliability and safety. For missions prior to the present Shuttle, safety assessments were thorough but qualitative, based on analyses such as failure modes and effects.[2] Possible reasons for the slowness to adopt quantitative methods include the doubt that the involved calculations are the best use of scarce labor and computer resources and the fear that quantitative methods offer the appearance of knowledge where knowledge does not exist (F. Fendell, TRW, personal communication, Nov. 1991). Recently, however, interest has arisen, counter to the earlier skepticism, in the application of limited-scope probabilistic risk assessments (PRA) to spacecraft.[3] In the past year, NASA has announced that a PRA will be conducted on the Shuttle systems to determine risk priorities and potential safety improvements.[4]

Fire Hazards and the Space Station

Previous space-field risk assessments usually had cursory treatments of fire hazards because of a belief that the probability of an internal fire is slight. Strict acceptance testing for onboard material selection ensured that very few, isolated flammable articles enter the spacecraft. In addition, experimental tests conducted under quiescent, low-gravity conditions in the Skylab space station indicated that fires spread very slowly in microgravity.[5] These assumptions are now shown to be optimistic even for the Shuttle, and they are certainly challenged by the increased fire-safety stresses anticipated in the operation of the Space Station. An initial safety review of the Space Station concept identified fire as a significant hazard among the major threats to the well-being of the station.[6] In the cited, comprehensive study, four approaches to fire-threat reduction were proposed: design to preclude (fire prevention), design to control (flammable isolation), protective devices (fire detection and suppression systems), and risk definition (minimum acceptance standards). For the risk definition, an optimization of risk, cost, and benefits established a realistic safety goal of a residual fire hazard that causes no injuries nor damage sufficient to suspend operations.

The maturity of the designs for the Space Station now warrants additional quantitative risk assessments. A study by Fuller and Halverson (cited by Kaplan[7]), though only partially completed, examined the consequences of six fire-initiation scenarios: electrical shorts/overloads, water-electrolysis unit failures, oxygen leaks, chemical reactions, payload-experiment failures, and improper crew or ground-control actions. A second independent study, still in progress, utilizes a PRA approach to calculate event probabilities and process times from initiating scenarios (wire overheating, for example) through threats (heat, smoke, and toxins) to alleviating responses (extinguishment).[8] The study is the first to include microgravity fire experiments to provide information on fire characteristics, emissions, and time constants for validation of the resulting risk assessment.

Operational Experience

Minor breakdowns in human-crew space missions that could progress into fires are by no means rare. In Shuttle missions, documented anomalies include five "incidents", at least six smoke detector false alarms, and at least five smoke detector built-in-test failures.[9] Thus, in 7969 hours of elapsed Shuttle mission time (data to October 1992), incidents have occurred on the average of once every 1600 hr of mission time. In the reported incidents, listed in Table 1, the crew saw smoke and embers in the STS-28 mission and detected odors in the other missions.[10,11] All incidents were subsequently identified as thermodegradation events caused by failures of wires or electrical components. None caused a smoke alarm to actuate. On STS-28, instrumentation did indicate a rise in smoke concentration, but the maximum concentration was below the prescribed alarm setpoint. The cited incidents never spread beyond the breakdown source, most likely a credit to the Shuttle material controls and the prompt circuit-isolating response of the crew.

One may plausibly predict the same rate of fire-precursor incidents on the Space Station. One may also predict that the crew will be able to isolate the breakdown source initially, with further control through fire-extinguisher use, if this becomes necessary. Space Station fire protection is complicated, however, by the possibility of an incident occurring in an untended period, for example, between the assembly missions. The untended station

Table 1. Shuttle Fire-Risk Experience.

Mission	Date	Incident	Result	Response
STS-6	Apr. 1983	Wires fused near material processing unit; crew detected an odor	No atmospheric contamination measured	No alarm
STS-28	Aug. 1989	Cable strain at connector to teleprinter caused insulation failure and electrical short circuit; crew detected a few embers and smoke	Smoke and particle concentration recorded	Circuit breaker did not open; no alarm
STS-35	Dec. 1990	Overheated resistor in digital display unit; crew detected an odor	No atmospheric contamination measured	No alarm
STS-40	June 1991	Refrigerator-freezer fan motor failed; crew noted an irritating odor	Atmospheric contamination identified post-flight	No alarm
STS-50	June 1992	Electronic capacitor in negative body pressure apparatus failed; crew detected an odor	No atmospheric contamination measured	No alarm

safety systems will be monitored remotely by the ground crews; and, upon an alarm, the operators will initiate the automated response cycle of electrical-power shutdown and suppressant release in the affected zone. Since this is the only option even for the probable minor, non-fire incidents, an alarm in an untended period may unnecessarily waste suppressant resources and possibly damage components.

KEY ISSUES IN SPACECRAFT FIRE SAFETY

Material Flammability Criteria

Pioneering tests conducted on the 1974 Skylab space station showed that, for typical spacecraft materials in normal gravity where vigorous, buoyancy-induced convective flows are always present, flame-spread rates are 1.5 to 10 times greater than those in quiescent, microgravity conditions.[5] The flame-spread rate in microgravity, however, has been shown to increase with forced-air flows (ventilation). For example, representative flame-spread rates for thin-paper samples determined in experiments conducted at the NASA Lewis Research Center ground-based facilities are 1.1 cm/s in normal gravity, 0.5 cm/s in quiescent microgravity conditions, and 1.0 cm/s in forced-flow microgravity.[12,13] The latter rate was attained with a 6 cm/s atmospheric flow opposed to the flame spread direction — a minimal ventilation velocity. Similarly, the limiting oxygen concentration, or the lowest atmospheric content in which flames will spread, was 16.5% in normal gravity, 21% in quiescent microgravity, and 16% in forced-flow microgravity.

As a practical necessity, materials for use in spacecraft must be qualified by normal-gravity acceptance tests. A standard NASA test for sheet materials determines the resistance to the upward spread of flame (NASA NHB 8060.1C, Upward Flammability Test). The buoyant air flow in the direction of the flame spread provides a "worst-case" environment in normal gravity and an assumed safety factor for microgravity applications. A recent study suggests possible improvements in the standard test to aid flammability predictions,[14] but no study as yet derives correlations of normal-gravity to corresponding microgravity flammability. In addition, common articles of paper, fabric, and plastics that are clearly flammable must be accepted in spacecraft for lack of suitable substitutes. Usage agreements for these articles demand strict control of quantity, configuration, spacing, and storage. Whether these special provisions can be continuously enforced during the long-duration missions of the Space Station is a concern for safety planning.

Spacecraft Atmosphere

The atmosphere of the Shuttle Orbiter and the proposed Space Station consists of air at ordinary sea-level total pressure and oxygen concentration (21 vol%). Prior to an extravehicular activity (EVA), the atmosphere is modified by removing some of the nitrogen but not the oxygen. This change decreases the total pressure, but it also increases the oxygen concentration to a maximum of 30 vol%. The modified atmosphere permits the crew to acclimate rapidly in low-pressure space suits without the need for prolonged prebreathing times to reduce blood nitrogen levels and prevent decompression sickness.

An increased concentration of oxygen in the atmosphere can accelerate flammability considerably and promote flame spread for some materials otherwise "non-flammable" in air. A review of 766 selected materials with acceptable flame-spread resistance (in normal gravity) under air showed only 654 had acceptable fire-spread resistance under an enriched 30%-O_2 atmosphere.[15] The NASA Lewis studies cited in the previous section also noted the strong influence of atmospheric oxygen on flame-spread rates in microgravity. For example, data for thin paper show that the flame-spread rate is increased by a factor of approximately 1.7 in the EVA 30-vol%-O_2 atmosphere compared to that in air.[11,12]

In contrast to the hazards of increased-oxygen-concentration atmospheres, atmospheres with reduced-oxygen concentrations have been shown to offer both life-support and fire-protection advantages.[16] In particular, a reduced-oxygen (or excess-nitrogen) atmosphere in the untended periods of the Space Station would essentially eliminate the probability of incipient fires requiring the automatic discharge of extinguishant. A systems analysis must determine the trade-off of the costs of atmospheric nitrogen loss and replenishment prior to each crew revisit to the savings in reducing the likelihood of untended-period alarms and their wasteful consequences.

Fire Detection

The fire-detection system under consideration for the Space Station consists of photoelectric smoke detectors installed to monitor local zones. The sensors use a conventional principle based on the response to the obscuration or scattering of a light beam by smoke particles in the atmosphere flowing through a sampling duct.[17] Ground-based, smoke-chamber development tests have established an alarm setpoint of 1.5%/m light obscuration for early warning of incipient fires and smoldering. Whether this setpoint is suitable for rapid recognition of fire "signatures" in microgravity is not known. Small-scale test data do indicate that the average size and concentration of smoke particles from microgravity fires may vary considerably from those of normal-gravity fires.[18] The obvious safety factor in setting the alarm threshold at a low smoke concentration can cause more frequent false alarms from detector electronic noise or benign atmospheric pollutants (dusts). Other detection-system requirements, such as alarm-confirmation and failure-tolerance criteria, and even the zone volume specification for an optimum number and location of sensors in the station, are not yet established with any confidence.

Fire Suppression

Proposed fire suppression for the Space Station consists of a primary fixed system for remotely actuated discharge of carbon dioxide agent and a secondary system of portable carbon dioxide fire extinguishers. Storage quantities and release rates are sized to achieve a zone flooding concentration of 50 vol% CO_2, a level based on terrestrial standards and developmental-test results. The Space Station suppression system has a single-failure tolerance; *i.e.*, the primary system is backed by the portable fire extinguishers. In the untended periods, however, the only alternative upon failure of the primary suppression system is in the remotely actuated venting of the spacecraft atmosphere to space. The extinguishment of fires by venting to a sufficiently low total pressure has been demonstrated in small-scale microgravity tests.[5,11] The flow created by venting, however, was shown to stimulate the growth of the microgravity fire temporarily.[11]

Analyses suggest that the mechanisms and rates of fire suppression in low gravity may differ substantially from those in terrestrial environments.[19] Until more data are available, conservative requirements must govern the spacecraft designs. It is thus possible that the proposed Space Station suppressant concentrations may be insufficient for effective rapid extinguishment or, on the contrary, excessive and wasteful.

Post-Fire Restoration

The proposed concentrations of carbon dioxide for suppression by flooding the unsealed racks or other zones can produce toxic concentrations through leakage into the Space Station cabin atmosphere. The prompt removal of excess agent and combustion products from the spacecraft atmosphere during and after a fire is beyond the standard capabilities of the environmental-control system. Localized venting or dedicated emergency contaminant-removal systems are under study, but these methods require more development. The long-term, subtle effects of toxic and corrosive fire by-products on both the crew health and equipment performance must also be considered in post-fire management.

CONCLUDING REMARKS CONCERNING DESIGN AND RESEARCH

The Space Station is now undergoing an extensive restructuring in design and operations, although it is unlikely that the basic requirements for fire protection will change. Fire prevention, detection, and suppression provisions for current spacecraft and the Space Station are adapted from accepted practices in terrestrial fire safety. Shuttle experience indicates that current fire protection is adequate. Nevertheless, the uncertainties in the nature of fires and the effectiveness of response techniques in microgravity require that system designs be conservative with high safety factors. Quantitative risk assessments in progress to evaluate the probabilities and consequences of fire-related incidents promise results to define practical safety levels and improve system efficiency. For successful analyses, a primary need is information on the correlation of normal-gravity acceptance-test data to realistic material flammability and flame-spread rates in low gravity. The current small-scale tests in ventilated, microgravity environments are to be augmented with practical experiments on representative, thick material sections (requiring Shuttle accommodations). Other needs are data to optimize fire-detection alarm setpoints and minimum suppressant concentration and flow rates, to establish alarm confirmation and false-alarm rejection logic, to provide failure-tolerance alternatives for untended periods, and to develop post-fire cleanup techniques.

SUMMARY

The unique, low-gravity environment in orbiting spacecraft greatly influences the processes of fire initiation, spread, and suppression. For efficient and improved fire-safety management in future spacecraft, risk assessments are required that incorporate specific information on spacecraft material selection, spacecraft atmospheres, fire detection, fire suppression, and post-fire restoration.

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A fire in the inhabited portion of a spacecraft is a greatly feared hazard, but fire protection in space operations is complicated by two factors. First, the spacecraft cabin is an enclosed volume, which limits the resources for fire fighting and the options for crew escape. Second, an orbiting spacecraft experiences a balance of forces, creating a near-zero-gravity (microgravity) environment that profoundly affects the characteristics of fire initiation, spread, and suppression. The current Shuttle Orbiter is protected by a fire-detection and suppression system whose requirements are derived of necessity from accepted terrestrial and aircraft standards. While experience has shown that Shuttle fire safety is adequate, designers recognize that improved systems to respond specifically to microgravity fire characteristics are highly desirable. Innovative technology is particularly advisable for the Space Station, a forthcoming space community with a complex configuration and long-duration orbital missions, in which the effectiveness of current fire-protection systems is unpredictable. This paper briefly reviews the development of risk assessments to evaluate the probabilities and consequences of fire incidents in spacecraft. It further discusses the important unresolved issues and needs for improved fire safety in the Space Station, including those of material selection, spacecraft atmospheres, fire detection, fire suppression, and post-fire restoration.

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