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Progress in Fire Detection and Suppression Technology for Future Space Missions

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PROGRESS IN FIRE DETECTION AND SUPPRESSION TECHNOLOGY FOR FUTURE SPACE MISSIONS

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Abstract

Fire intervention technology (detection and suppression) is a critical part of the strategy of spacecraft fire safety. The paper reviews the status, trends, and issues in fire intervention, particularly the technology applied to the protection of the International Space Station and future missions beyond Earth orbit. An important contribution to improvements in spacecraft fire safety is the understanding of the behavior of fires in the non-convective (microgravity) environment of Earth-orbiting and planetary-transit spacecraft. A key finding is the strong influence of ventilation flow on flame characteristics, flammability limits, and flame suppression in microgravity. Knowledge of these flow effects will aid the development of effective processes for fire response and technology for fire suppression.

Introduction

The major approach to fire protection in current and advanced human-crew spacecraft is through prevention. Thus, fire safety relies strongly on the selection of materials proven to be fire-resistant through analysis and testing.[1] The complete strategy of fire protection, however, also includes technology for the detection, response, and suppression of fires, even if the probability of the occurrence of a spreading fire in spacecraft is extremely small.[2]

Improvements in the current fire-safety technology may likely be necessary for the International Space Station (ISS) and future human-crew missions beyond low-Earth orbit. Severe limitations on mass and power and the need for monitoring over long periods of continuous spacecraft operation are two of the obvious challenges to fire safety in future missions. The original space-station design concepts included a "racetrack" configuration for alternative escape paths, multiple-sensor detector systems, and fixed, remotely operated suppression systems, all of which were removed for practical reasons in the restructuring of the ISS.[3] The inclusion of Russian modules in the new structure also introduces non-conforming designs and technology for fire detection and suppression (fig. 1). The Russian fire-protection provisions are by no means inferior to those of the other ISS partners, yet the lack of commonality among fire protection can be a threat to safety.[4]

This paper is a review of advances in the science and technology of fire detection, response, and suppression for spacecraft, based upon the open literature, including relevant findings from microgravity combustion analyses and experiments.

Spacecraft Fire-Safety Background

General Strategy

The basic approach to minimize fire hazards is through prevention, which implies the elimination of one of the three fire-causing factors of fuel, oxygen, and ignition energy. Prevention is never absolute, however. Thus, the overall strategy of fire safety must include fire detection and suppression.

Spacecraft fire-safety practices are, to a certain extent, modeled on accepted standards for transportation systems, particularly those for aircraft. Aircraft and spacecraft have similar safety issues, i.e., confined space, hostile outside environment, and restricted mass, volume, and power availability for fire-intervention systems. Spacecraft, of course, have unique safety challenges in the high value of individual missions and the very limited experience for establishing predictive risk assessments. Above all, the non-convective (microgravity) environment in orbiting and planetary-transit spacecraft strongly influences fire characteristics and the operation of technology to respond to fires.[5]

Fire Characteristics in Low Gravity

Microgravity is an impediment to spacecraft operations and a challenge to safety, but it does offer an environment enabling the study of basic and applied

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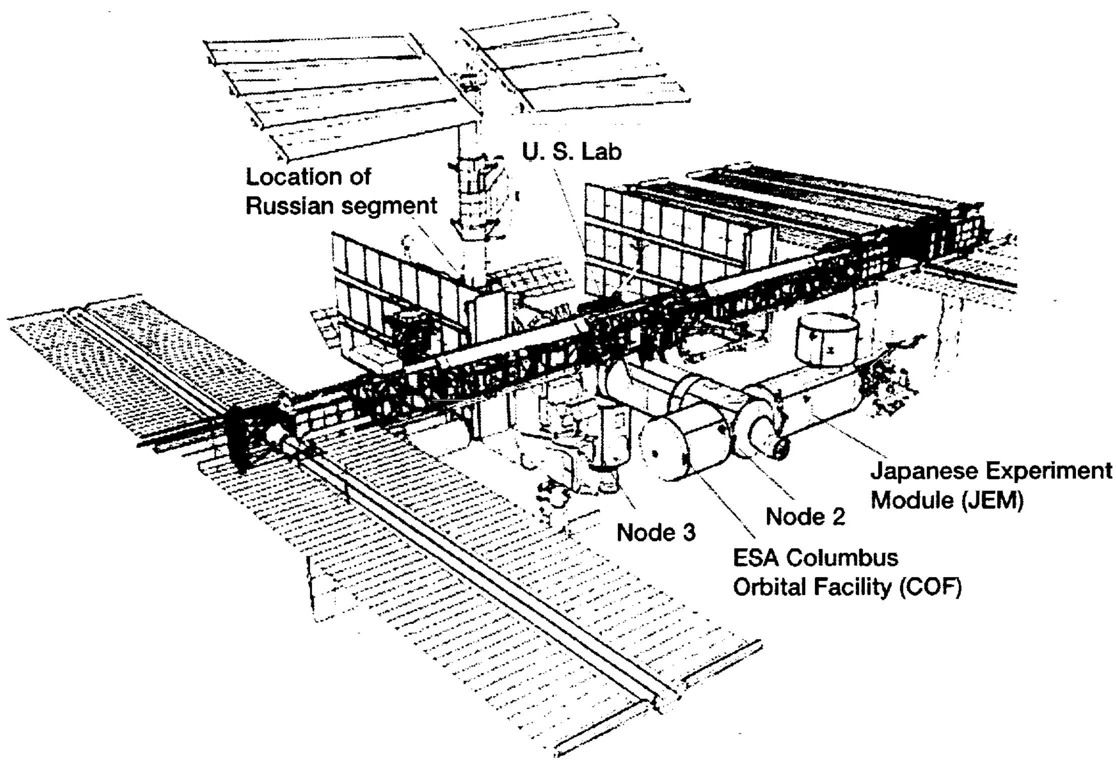

Figure 1.—Current International Space Station Design at Assemble Complete.

combustion processes. Microgravity research permits simplified representation and scaling, greatly increasing the range of fundamental fire data, including those applicable to conventional ground environments.

There is now a growing body of information from research on combustion in non-buoyant (microgravity) environments. Table 1 lists several projects conducted on the U.S. Space Transportation System (STS) Shuttle, its payload-bay laboratories, or *Mir*, which have furnished information of potential value to spacecraft fire-safety technology. These projects offer observations and measurements of flammability, flame spread, and smoke characteristics from burning sheet and slab materials in microgravity environments.

The data obtained from scientific research on microgravity combustion have contributed greatly to the current understanding of the important characteristics of fires in low gravity. Key features of low-gravity fires relevant to fire-safety technology are summarized in Table 2. Flammability and flame-spread rate in microgravity are particularly sensitive to atmospheric flow. Flames propagate poorly in truly quiescent conditions, but they are enhanced vigorously by low-rate atmospheric flows (velocities up to about 20 cm/s). Ventilation is not the only source of flame-stimulating flow. Some burning plastic materials may induce flow to continue combustion through the action of boiling and vapor-jet ejection.[6]

Fire Detection Technology

Status of Fire Detection in Human-Crew Spacecraft

Sensing by the crew is no doubt the most reliable means of early warning of incipient fires in spacecraft; and, in the first human-crew U.S. space missions (Mercury, Gemini, and Apollo), this was the only way to detect fires.[7] The complex and sometimes inaccessible volumes of current and advanced human-crew spacecraft require the addition of automated detection.[8] These detectors respond to fire "signatures", i.e., the environmental changes that are characteristic of fire precursors. Typical signatures are temperature rise, combustion gases, light and other radiation, particulates (smoke), pressure rise, and acoustic waves.

In current spacecraft, automated early warning of fire events is achieved through smoke detectors, using principles of light scattering or ionization-current interruption. The Shuttle has nine detectors of the aspirating ionization type. The U.S., European, Japanese, and Italian segments of the International Space Station (ISS) will have one or more detector units in each module that sense smoke through photoelectric light-beam obscuration and scattering (fig. 2). The ISS smoke detector is installed in some locations as spot types, or area monitors, and in other locations within airflow ducts as aspirating types, or duct monitors.

Table 1.—Selected experimental projects conducted in space flight, with results relevant to spacecraft fire safety.

Project	Description	Date
Solid-Surface Comb. Exper. (SSCE)	Burning of thin-paper and thick-PMMA fuels in quiescent environments to determine effects of oxygen concentration and total pressure on flame spread	1990 – 1998
Radiative Ign. and Transition to Spread Investigation (RITSI)	Burning of thin paper with central ignition and low-rate forced flow to determine effects of air flow on unconstrained 2- and 3-dimensional flame spread	1996
Diffusive and Rad. Transport in Fires (DARTFire)	Burning of thick fuels under opposed flow and external heat flux to determine effects of flow and preheat on flame spread	1996 – 1997
Mir Experimental Verification of Material Flammability in Space	Burning of cylindrical plastic fuels under concurrent flow to determine flame characteristics and limiting flows for flame spread	1998
Forced Flow Flame Spread Test (FFFT)	Burning of flat and cylindrical cellulose and polyethylene fuels under concurrent flow and external heat flux to determine effects on flame length and spread rate	1996
Microgravity Smoldering Comb. (MSG)	Burning of bulk foamed plastics under flow to determine smolder rate and combustion-product evolution	1995 – 1996
Forced-Flow Ign. and Flame-Spread Test (FIST)	Evaluation of new method to measure ignition delay and flame spread in microgravity with flow and external heat flux	In prep.
Comparative Soot Diagnostics (CSD)	Evaluation of STS and ISS smoke-detector responses to pyrolysis, smoldering, and flaming fires in representative fuel samples	1996

Table 2.—Key features of fires in low gravity or microgravity.

Property	Trend	Remarks
Ignition	Promoted	•Thermally stressed components can overheat rapidly •Particulate spills form flammable aerosols that persist for long periods of time •Burning plastics eject hot material randomly & violently
Flame Appearance	Altered	•In quiescent environments, flames are often symmetrical in shape and nearly invisible •Under low rates of imposed air flow, flames intensify and become bright and sooty
Flammability and Flame-Spread Rate:→*Quiescent Conditions*	Reduced or extinguished	•Flames propagate slowly or extinguish, due to the accumulation of combustion products
Flammability and Flame-Spread Rate:→*Low-Flow Conditions*	Increased, in some cases to match or exceed normal-gravity levels	•Low-rate ventilating flows stimulate low-gravity fires and greatly extend their flammability range and flame-spread rates •Freely propagating flames tend to spread toward the "wind," or into the oxygen source
Detection "Signatures"	Altered	•Flames are often cooler and less radiant •Average size and range of soot-particle sizes are greater •Combustion-product nature and quantities are altered

While the ISS photoelectric detector mass of 1.5 kg is equivalent to that of the Shuttle ionization type, the ISS unit has advantages of a much lower power requirement (1.48 compared to 9 W), and a lack of moving parts.[9] The Russian Segment modules were designed independently of the balance of the ISS, and their fire-response systems are unique. The Functional Cargo Block (*Zarya*), placed in orbit November 1998, has ten ionization smoke detectors, which are similar in principle but not identical to those on the Shuttle. The Service Module (*Zvezda*), the next element to be assembled, will have photoelectric detectors, which are *Mir* designs that conform in principle but not in design to the types in the other ISS segments.

Fire Detection in Microgravity

In Table 2, the rows labeled "Flame Appearance" and "Detection 'Signatures" cover features of fire signatures observed in microgravity. These differences in fire characteristics compared to those in normal gravity strongly influence the sensing of incipient fires. Flames in near-quiescent or low-oxygen environments are often pale blue and almost invisible.[10] Under increased atmospheric flow rates or oxygen concentrations, the flames become brighter and yellow, presumably due to soot and smoke evolution. Figure 3 is an example in the form of a flammability map derived from measurements on burning PMMA in low gravity.[11] The map shows the zones of blue and yellow flames as functions of oxygen concentration and flow rate.

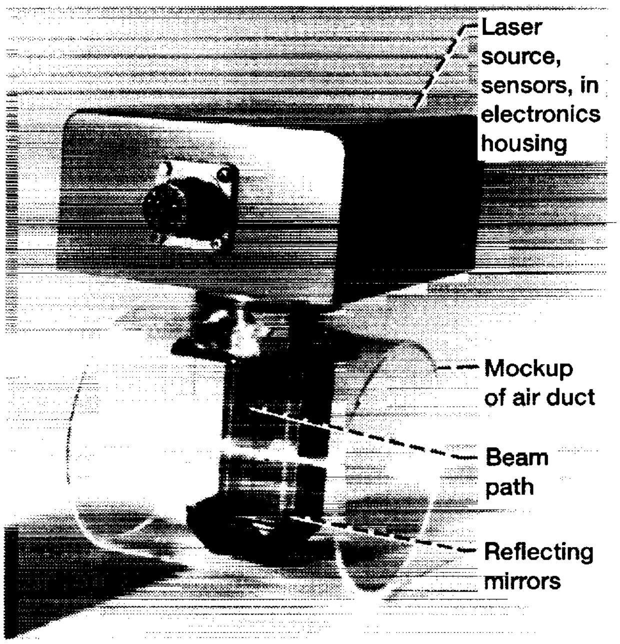

Figure 2.—Model of prototype photoelectric smoke detector installed on the U.S., European, Japanese, and Italian operational segments on the International Space Station.

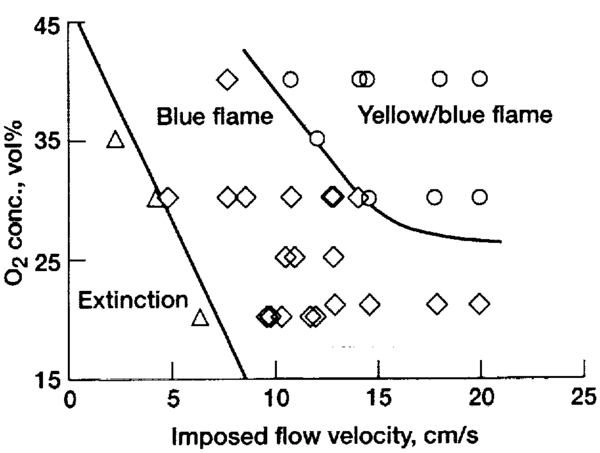

Figure 3.—Map of blue diffusion-controlled flames and blue/yellow convection zones for thick PMMA sheets burning in low gravity.

Experimental verification of smoke detection in microgravity was the objective of a Shuttle-based project, Comparative Smoke Diagnostics (CSD). This study examined the particulate emissions from typical, well-established pyrolysis or fire events in microgravity.[12] The sources include a burning candle and four overheated materials, namely, paper (flaming in some tests), silicone rubber, polytetrafluoroethylene-insulated wires, and polyimide-insulated wires. In the near field (i.e., within the same chamber as the smoke generators), smoke particulates are collected on thermophoretic grids for later analysis, and total smoke density is measured by laser-light extinction. In the far field (i.e., in a separate chamber connected by a pumped hose line), smoke-detector response is determined for a Shuttle (STS) detector and a prototype ISS detector in parallel.

Table 3.—Selected Examples of Responses of STS and ISS Smoke Detectors in Microgravity, from Comparative Soot Diagnostics Experiment.

Fuel	Condition	Time to Respond to an Arbitrary Set Point, sec	
		STS Detector	ISS Detector
Candle	Flaming	40	56
Paper	Flaming	54	20
Silicone Rubber	Smoldering	40	20
PTFE Wire	Pyrolyzing	39	30
Polyimide Wire	Pyrolyzing	25	14

In general, the ionization detector is sensitive to relatively small particles, and it is well suited for detecting a flaming fire. The photoelectric detector is sensitive to relatively large particles, and it is well suited for detecting smoldering fires. In microgravity, smoke particles tend to agglomerate due to the lack of buoyant motion, to form larger entities. This suggests that the ISS detector will respond faster than the STS detector in microgravity. Table 3 is a summary of selected data on response times for each detector to reach an arbitrary fraction of full scale for the smoldering and fire events in the CSD project. The measurements show that, despite changes in the nature of the smoke signatures in microgravity, both detectors have adequate, if not entirely optimal, response to the model signatures. These comparisons are qualitative because the signal of the ISS detector, a prototype, is amplified to match the assumed characteristics of the future flight model.

False Alarms

A recognized problem in fire-detection systems is that of false alarms, which can cause needless interruptions, waste of suppressant in automatic systems, and erosion of the confidence in the detection system. Cleary and Grosshandler[13] report that, in aircraft cargo compartments, false alarms are 100 times more frequent than true fire events. The Shuttle experience has been more favorable. Less than 20 false alarms or detector failures have been recorded in the 20 years of Shuttle operations.[14] In the same period, only five potential fire-causing incidents of component overheating or electrical short circuits occurred. In no case was the incipient-fire signature strong enough to cause a smoke detector to actuate, and the crew was able to recognize and correct the problem.[15]

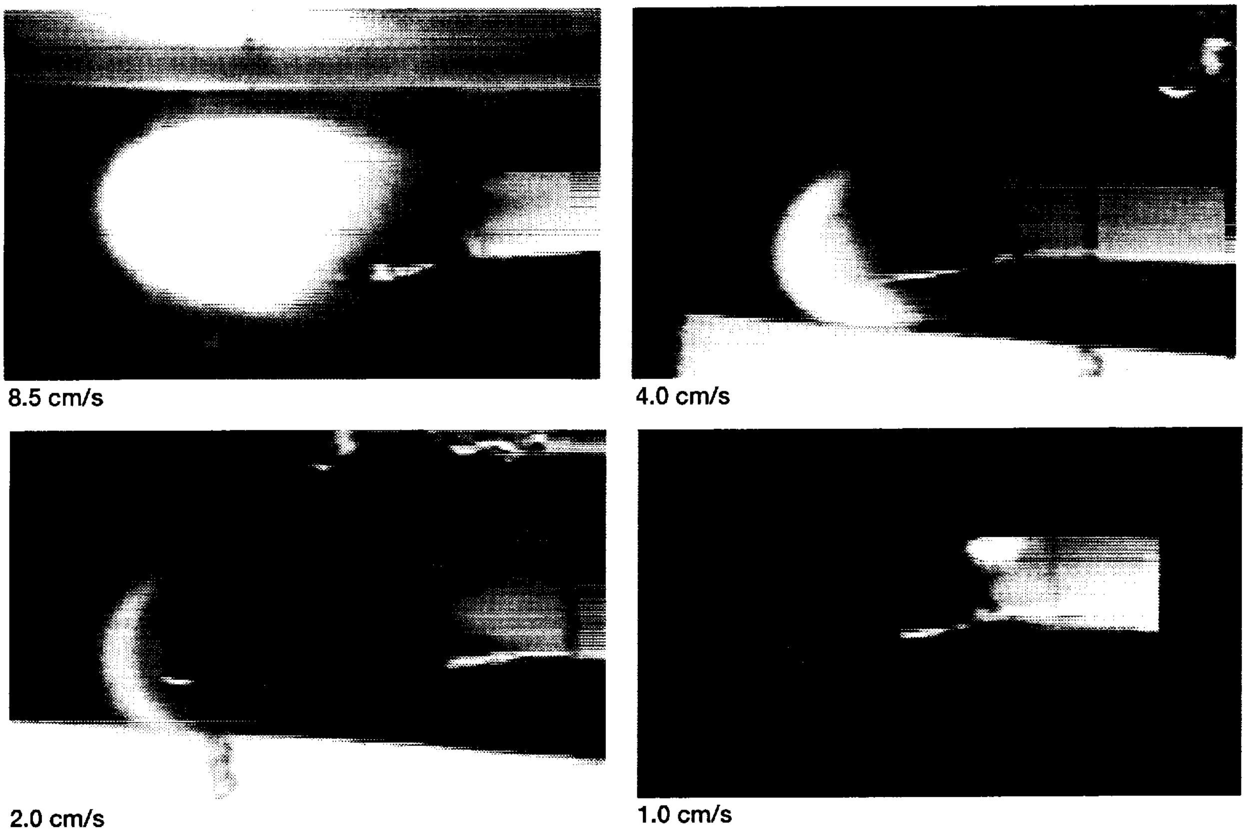

Figure 4.—Changes in flame appearance over polyethylene rod in microgravity, for concurrent air velocities shown.

Fire Detection by Atmospheric Sampling

Data on the rate of buildup of atmospheric signatures, particularly carbon monoxide concentrations, can also provide early warning as a possible confirmation of the smoke detection. It is likely, due to changes in flame-zone temperatures in microgravity, that the composition and quantity of gaseous combustion products will differ from those in normal gravity. Early studies on smoldering indicated a greatly increased quantity of light-gas evolution in microgravity; but this finding appears to be strongly dependent on the experiment scale and conditions, and it was not observed in later tests.[16]

Continuous atmospheric sampling, to be used on the ISS primarily for air-quality monitoring,[17] has the promise of early warning of the buildup of carbon monoxide concentrations as a confirming indication of a fire event. More effective for interpretation of fire signatures than single-gas sampling is multiple-gas sensing. For example, combined CO/CO_2 detectors are shown in ground tests to discriminate among non-flaming fires, flaming fires, and non-fire events.[18]

Fire Detection from Flame Radiation

The original designs of the space station also included flame-radiation sensors in the end cones for overall monitoring of the open spaces of the modules.[19] The need to conserve mass and electric power eliminated these detectors from the ISS designs, but technology development continues in the European Space Agency on flame detectors for supplemental fire detection.[20]

Fire Response

Upon a verified fire alarm, the automated or manual crew response is to isolate the affected zone, removing power and local or general air circulation. It is assumed that, without forced ventilation flow, the microgravity fire will not propagate.

In most fire situations, research results verify that quiescent flames do self-extinguish. This behavior implies that a minimum atmospheric flow rate is necessary in low gravity to maintain fire propagation (and conversely to assure extinction). Values of the limiting forced flow for flame spread have been measured by Ivanov[21] for some common plastics burning in strip and cylindrical configurations. Interesting results on the effects of concurrent flow-rate change on flame appearance are illustrated in fig. 4. At the highest velocity of 8.5 cm/s, the flame over the polyethylene rod is bright and nearly white. At 4.0 cm/s, only the trailing (left) edge of the flame is bright and yellow. At 2.0 cm/s, a crescent of bright orange trails the otherwise pale blue flame. At 1.0 cm/s, the entire flame is pale violet and nearly invisible (the image is enhanced in the black-and-white reproduction). The limiting flow velocity for flame propagation for this fuel is 0.5 cm/s. Upon complete cessation of air flow, flames are suppressed in 5 to 20 seconds.

Note that limiting flows for relatively flammable materials are very low. Self-induced flows may be sufficient to continue combustion.[6] An interesting case is that of a candle. In a series of experiments on *Mir*, U.S. investigators found that a candle would continue to burn in a quiescent environment for several minutes.[22] Thus, removal of air flow upon fire detection is a necessary response, but it is not always sufficient for control of the incipient fire.

Fire Suppression Technology

Status of Fire Suppression in Human-Crew Spacecraft

Fire suppression may rarely be needed in space operations, but it must be made available for the security of the crew and the mission integrity. Human-crew spacecraft have always been equipped with some means of fire extinguishment.[7] In the Mercury and Gemini spacecraft, a water gun used for food reconstitution was designated for the secondary purpose of an emergency fire extinguisher.[23] Dedicated fire extinguishers became available in the next generation of space missions. The Apollo spacecraft, for example, had extinguishers that generated a stable water-gas mixture propelled by inert Freon and nitrogen gases.

The Shuttle and its payload-bay laboratories have extinguishers charged with gaseous Halon 1301 (bromotrifluoromethane).[8] Portable fire extinguishers have nozzles suitable for streaming discharge into open spaces or insertion through cover ports for flooding discharge within racks. The Shuttle also has a fixed, remotely operated Halon 1301 system, for use during critical periods, such as reentry, when the mobility of the crew is limited.

The non-Russian segments of the ISS have portable fire extinguishers charged with carbon dioxide. No centralized, fixed system is planned.[3] The Russian segment of the ISS has water-foam extinguishers, based on technology already in service in other Russian spacecraft.

Fire Suppression in Microgravity

A key concern is that of the minimum quantity of extinguishant (or the resulting minimum oxygen concentration) needed to ensure suppression. The understanding of the process of fire suppression in microgravity—particularly with regard to the practical technology for fire extinguishment—is very limited.

The minimum requirements for carbon dioxide as a flame suppressant in spacecraft are based on the resulting oxygen concentration in the flame zone. The ISS suppression system is designed to release sufficient carbon dioxide (50 percent minimum) to reduce the ambient oxygen in an affected compartment to half its original concentration within 60 seconds.[4] On the other hand, the National Fire Protection Association standard NFPA 12 permits a minimum concentration of 34 percent carbon dioxide for flooding applications. Table 4 shows the resulting oxygen concentrations upon carbon dioxide flooding according to the NASA and NFPA requirements and compares them to extinguishment test results. Three cases of initial atmospheric oxygen concentrations—21 percent (air), 24 percent (the ISS maximum tolerance),

Table 4.—Examples of Atmospheric Oxygen Reduction Necessary for Fire Extinguishment.

Initial atmospheric O_2 concentration	21% (air)	24% (tolerance limit)	30% (prebreathing)
Final O_2 concentration, vol %, attained after dilution by CO_2 discharge, based on			
NASA requirements of 50% CO_2	10.5	12	15
NFPA 12 requirements of 34% CO_2	13.9	16	20
Minimum O_2 concentration, vol %, from ground experiments, needed for extinguishment of the following fuels			
Polyurethane foam strip	19 – 20	18 – 20	22.5 – 24
Nylon Velcro	18 – 19	18 – 20	19.5 – 21
Minimum O_2 concentration, vol %, from experiments on flammability limits of tissue-paper fuels, in the following cases[a]			
Normal gravity, downward spread[b]	16.5		
Microgravity, quiescent	21		
Microgravity, opposed flow[c]	15		
Microgravity, concurrent flow[c]	13		
Partial gravity (0.15 to 0.4 g)[b]	15		

[a]Initial atmospheric O_2 concentration immaterial for these measurements.
[b]Natural buoyant flow present in normal and partial gravity.
[c]Imposed flow in microgravity always less than 8 cm/s.

and 30 percent (the ISS prebreathing atmosphere prior to an extravehicular activity)—and two sets of experimental data are shown. The first set of data is from normal-gravity qualifying tests for the ISS system. Minimum oxygen concentrations for fire suppression are given for a foam and a Velcro material.[24] The second set of data is for flammability limits (minimum oxygen concentrations for flame propagation) of tissue-paper fuels in normal gravity, partial gravity, and microgravity, with and without imposed flows.[25–27]

The data in Table 4 are not strictly comparable, because of differences among the tests in the fuels, gravitational control, and mechanism of flame suppression. Some interesting observations can be made, nevertheless. First, the qualifying tests show that the NASA and NFPA requirements are both adequate for reducing the oxygen concentration below the experimental flammability limits, although the NFPA requirement is marginal applied to the 30 percent-initial-oxygen case. Second, the tests with flammable paper fuels show that the stricter NASA requirements are necessary to control in scenarios of fires under forced-flow or buoyancy-aided microgravity conditions. The results emphasize the strong fire-enhancing action of low flows in microgravity.

The extinguishing action of carbon dioxide can be through thermal effects—reduction of the temperature of the fuel surface and the flame zone—in addition to oxygen dilution. Pitts, et al.[28] estimated the extinguishing concentration of carbon dioxide as a thermal agent by calculating the flame-temperature reduction for a model methane/air diffusion flame. The addition of about 22-vol% carbon dioxide is sufficient to reduce the flame temperature to an assumed minimum to quench the flame reaction. Nevertheless, for solid-material fires, the conservative approach, verified by experiment, is to consider only oxygen dilution in defining the minimum agent quantity for guaranteed suppression.

Halon Phaseout and Replacement

The manufacture and new uses of Halon 1301, the Shuttle agent, is now prohibited by international protocol, since it is a stratospheric ozone-layer depleter. Halon 1301 is a chemical agent, i.e., one that inhibits combustion by chemical reactions to remove free-radical intermediates in the reaction zone. While many Halon replacements have great promise in terms of environmental acceptance, low cost, low toxicity, among other qualities, they rarely approach the extinguishing efficiency of Halon 1301. For example, HFC-227ea, heptafluoropropane, a highly regarded Halon replacement, requires about twice the discharge quantity as Halon 1301, based on reference tests.[29]

There are no plans to remove Halon 1301 from the Shuttle supply, but NASA has been actively engaged for the past ten years in a program to phase out Halon in ground and launch facilities through improved installation, leak prevention, and maintenance.[30]

Suppression of Oxygen-Generator Fires

An event on *Mir* in February 1997 involved a fire from a failed chemical oxygen generator.[21] The fire fortunately caused little damage and no injuries, but it was difficult to control. Module and atmospheric cleanup occupied the attention of the crew for several days. Chemical oxygen generators are not currently planned for use in the ISS U.S. On-Orbit Segment, but they are backup oxygen sources in the Russian Segment. Ground investigations of ignited generators, induced by cassette contamination or steel-shell failure, show that water-based foam, the agent used in the Mir incident, is the most effective extinguishing agent, somewhat superior to water alone. The foam must be applied directly to the surface of the generating cassette. Carbon dioxide is completely ineffective; in fact, it is shown to enhance the fire.[31]

Other Agents for Spacecraft Fire Suppression

For small, inhabited volumes in spacecraft, for example the ISS airlock, carbon dioxide discharge can be hazardous, exceeding toxic limits. An alternative to both Halon and carbon dioxide is nitrogen. Nitrogen is inert, available, and non-toxic, but it is less efficient as a suppression agent than carbon dioxide.[8]

Water-based mists and foams to replace gaseous agents in spacecraft have advocates.[32] These mixed-phase suppressants (noted above in connection with oxygen-generator fires) can be very effective, providing suppression through flame cooling as well as oxygen dilution. The ISS Russian Segment will retain the *Mir*-type aqueous-foam suppression systems.[33] The performance of mixed-phase foams for fire suppression in low gravity has been investigated in airplane tests.[10] Although the foam penetration is different in low gravity compared to normal gravity, the foam does stick to surfaces, and it successfully suppresses fires by oxygen exclusion. Non-gaseous agents, however, have an obvious disadvantage in the difficulty of their removal from the atmosphere and surfaces after fire control, and their inadvertent discharge can seriously disrupt space station activities.

Pressure Reduction and Venting for Extinguishment

The ISS has the option of abandoning a module, closing its hatches, and venting the module, as a means of controlling a difficult or inaccessible fire. A vent/relief valve is designed to reduce the pressure in the U.S. Laboratory Module, in response to two emergency scenarios. To suppress a fire, depressurization is to reach a limit of 6.9 kPa in 10 min. To remove a hazardous atmosphere, depressurization is to reach a limit of 2.8 kPa in 24 hr. These performance goals can be attained, at least as demonstrated by flow and heat-transfer modeling.[34]

Studies in low gravity have investigated the effects of the rate of depressurization and the final pressure on fire suppression. These tests determined the low-pressure flame characteristics of a PMMA cylinder ignited along its axis with atmospheric crossflow.[35] Figure 5 presents a combination of experimental data and analytical results, showing the depressurization boundary for flame suppression. Note that the low-gravity suppression becomes more difficult with increasing fuel temperature. The effect of flow is variable. Extinction is most difficult around 10 cm/s, and the boundary rises to higher pressures (less depressurization needed) for greater or lesser flow velocities.

These low-gravity experiments and models suggest that, if a fire is to be controlled by depressurization, the pressure in the affected module should be decreased rapidly, inducing a high velocity and limiting the flame-zone heating. Slow depressurization can drive the final pressure to lower limits and make suppression difficult.

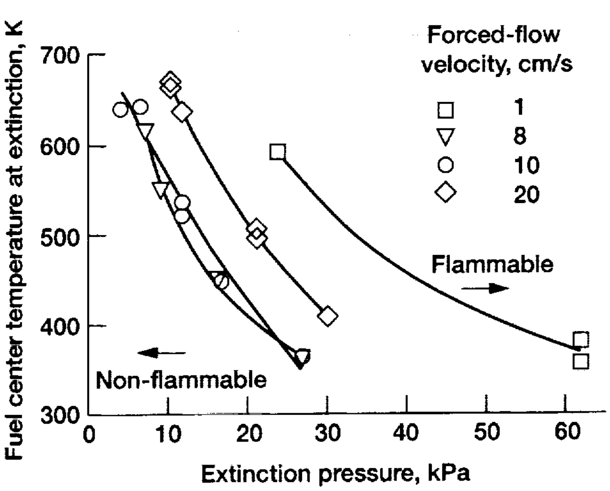

Figure 5.—Flame extinction boundaries for depressurization of PMMA cylindrical fuel at different forced flow velocities in low gravity. Data for 10 cm/s are experimental; others are calculated.

Post-fire Actions

Determining that a fire is completely extinguished in a spacecraft fire scenario is by no means straightforward. Since burned material remains hot in the non-convective environment, embers may reignite if prematurely exposed to fresh air. Both the U.S. Solid Surface Combustion Experiment (SSCE) space-flight and European Space Agency airplane tests demonstrated that, in low gravity, paper fuels are not completely consumed as flame passes; hence, reignition after apparent suppression is a possibility.[36,37]

Considerable cleanup will be required after all fire events, minor or major. Atmospheric revitalization to remove even trace quantities of fire and extinguishment contamination may tax the environmental controls and require the use of portable air-breathing equipment for lengthy periods of time. Even after nominal conditions are restored, the subtle toxic and corrosive aftereffects of the fire on equipment, systems, and payloads must be recognized and appropriately controlled.

Fire Safety For Payloads

A serious concern in fire safety on the ISS and in laboratory modules carried on the STS, is in the protection of payloads, particularly those contained in racks (fig. 6). Payloads may include furnaces, energetic experiments, and sensitive biological systems, all potential sources of fire threats.

Proposed techniques for payload fire detection and response include parameter monitoring (use of continuous data recording for interpretation as fire signatures) and automated cooling-air shutoff. A specific example of proposed fire protection for an ISS payload is that of the

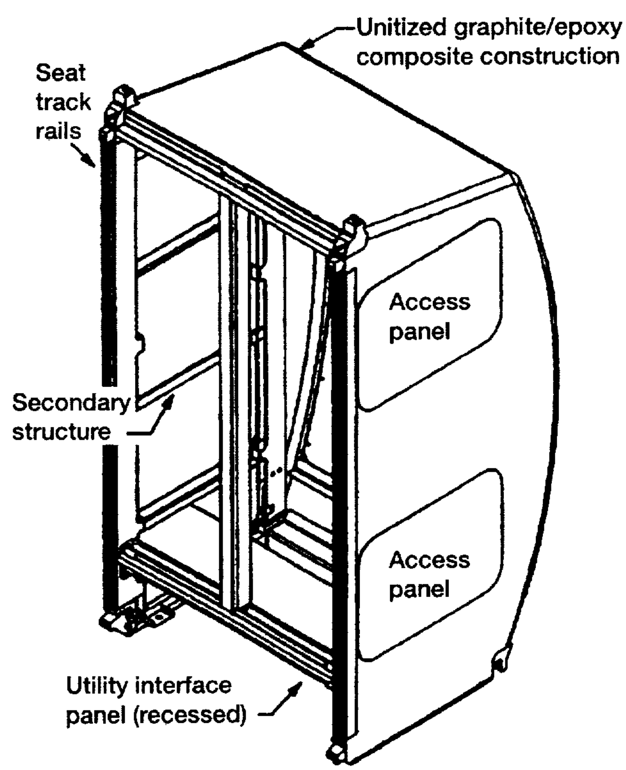

Figure 6.—Sketch of standard rack unit for systems or payloads on the International Space Station.

design for the Combustion Integrated Rack (CIR).[38] The CIR will serve as a common facility to provide the majority of chamber, diagnostics, flow, control, and power functions for customized combustion-experiment packages (fig. 7). The CIR fire protection is through a standard ISS smoke detector mounted within the internal cooling-air flow path and a rack door port, identical to the Shuttle design, for insertion of the portable fire extinguisher nozzle. The CIR will also have a local indication for the smoke alarm and automated and manual power shutoff in the event of an alarm.

Missions Beyond Earth Orbit

Fire-Safety Needs

Missions beyond Earth orbit (Martian and Lunar expeditions, as examples) can be considered in terms of two phases, the travel or transit phase, and the surface-base or habitat phases. For the transit phase, practical travel to the Moon or Mars must assume flight, for the most part, that is unpowered and without artificial gravity. Thus, the environment in the transit phases of these journeys is microgravity, identical to the environment of Earth-orbiting spacecraft. Fire protection on these missions will be a significant safety concern, more critical than for orbiting stations. Stores of suppressant and atmospheric diluents are more limited, long missions imply more accumulated wastes and possible relaxation of crew vigilance, and consultation and emergency communications with Earth controllers may be of poor quality and delayed. A favorable provision for fire protection is the proposed isolation chamber for shielding against solar-particle events,[39] which can be a secure refuge, available for directing remote fire-control operations (including venting and repressurization).

For the habitat phases, the crew and systems are exposed to a local gravitational acceleration that is greater than microgravity but less than that of the Earth (normal gravity). For Mars, this "partial gravity" level is 3.72 m/s^2, or 0.380 that of normal gravity. For the Moon, the gravitational level is 1.62 m/s^2, or 0.165 that of normal gravity.

Fire Safety in Partial Gravity

The current understanding of the effect of partial gravity on fire behavior is based on analyses and limited experiments. Parabolic airplane trajectories can create a short-time period of accelerations ranging from 0.01 to 0.6 g. Results of tests on the burning of thin-paper fuels were used to construct a flammability map of the limiting-oxygen concentrations that support flame spread as functions of gravitational level.[27]

The unusual finding of these studies is that the fuels exhibit a maximum in their flammability behavior in the partial-gravity range. That is, the flammability range increases to a maximum between normal-gravity and microgravity levels. (A typical value is included in Table 4.) The flame-spread rate also attains a maximum in this gravity range. Results from these tests at selected fuel and test conditions indicate that the partial-gravity fire maxima occur roughly over the range bracketing the levels of concern for missions beyond Earth orbit, namely, 0.15 to 0.4 of normal gravity. The influence of partial gravity on flammability and flame-spread rates is believed to be caused by generation of optimum buoyant flow velocities at these low but finite convective environments. This

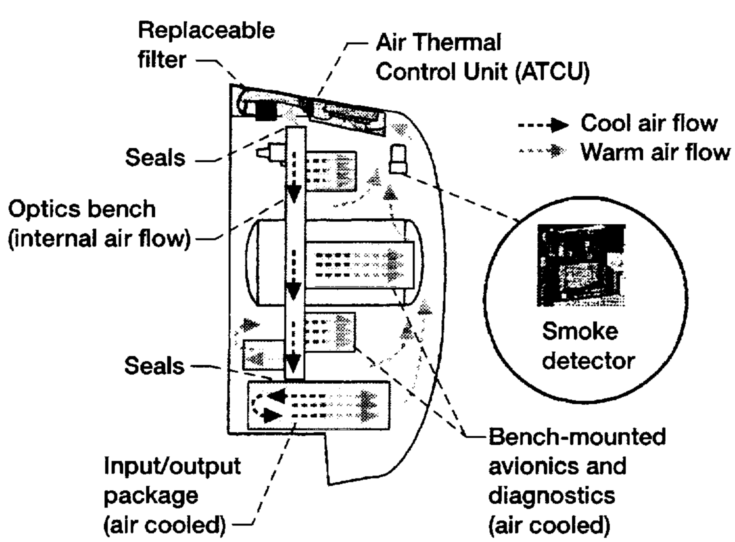

Figure 7.—Sketch of combustion integrated rack cooling-air flow patterns and smoke-detector installation.

phenomenon is comparable to the enhancement of flame spread by low-velocity forced flows in microgravity.

Other Fire-Safety Concerns

A reduced-pressure, enriched-oxygen atmosphere is being considered for both the transit and habitat phases of missions beyond low-Earth orbits in order to minimize the mass of nitrogen or other diluents carried.[40] As noted, higher oxygen concentrations affect fire prevention by decreasing the number of fire-resistant materials and increasing the flammability of the waivered exceptions, and they affect fire control by stimulating low-gravity combustion. In the habitat phase, the influences of Martian dust on surfaces or entering the atmosphere on flammability and smoke detection are presently unknown.

Conclusions

This paper is a review of the advances in the science and technology of fire detection, response, and suppression for spacecraft, based on information from the current literature. It must be noted that the established requirements and operations in spacecraft have been effective in maintaining fire safety, as tested by experience in the Space Transportation System. Nevertheless, there is need for improvement. Current standards (verified by normal-gravity testing only, to a great extent) may be far from optimal approaches, in terms of efficiency and safety margins. Future human-crew missions in the International Space Station and beyond Earth orbit may demand innovations in fire protection to meet new possibilities of fire scenarios in unusual, complex, and long-duration operations. In extraterrestrial habitats, studies show that fire behavior in reduced gravity cannot be quantified by linear interpolation between findings in microgravity and normal gravity. Thus, spacecraft fire safety will continue to depend strongly on the contributions from microgravity-combustion research.

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Fire intervention technology (detection and suppression) is a critical part of the strategy of spacecraft fire safety. The paper reviews the status, trends, and issues in fire intervention, particularly the technology applied to the protection of the International Space Station and future missions beyond Earth orbit. An important contribution to improvements in spacecraft fire safety is the understanding of the behavior of fires in the non-convective (microgravity) environment of Earth-orbiting and planetary-transit spacecraft. A key finding is the strong influence of ventilation flow on flame characteristics, flammability limits, and flame suppression in microgravity. Knowledge of these flow effects will aid the development of effective processes for fire response and technology for fire suppression.

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