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Robert Friedman, Brian Jackson, and Sandra Olson
Glenn Research Center, Cleveland, Ohio

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TESTING AND SELECTION OF FIRE-RESISTANT MATERIALS FOR SPACECRAFT USE

Robert Friedman, Brian Jackson, and Sandra Olson
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

ABSTRACT

Spacecraft fire-safety strategy emphasizes prevention, mostly through the selection of onboard items classified according to their fire resistance. The principal NASA acceptance tests described in this paper assess the flammability of materials and components under "worst-case" normal-gravity conditions of upward flame spread in controlled-oxygen atmospheres. Tests conducted on the ground, however, cannot duplicate the unique fire characteristics in the nonbuoyant low-gravity environment of orbiting spacecraft. Research shows that flammability and fire-spread rates in low gravity are sensitive to forced convection (ventilation flows) and atmospheric-oxygen concentration. These research results are helping to define new material-screening test methods that will better evaluate material performance in spacecraft.

KEY WORDS: Fire, Spacecraft, Testing/Evaluation

1. INTRODUCTION

Fire is a greatly feared hazard in the confined enclosures of human-crew spacecraft. A fire event must be controlled in place by the crew, since guidance from ground controllers is not always available, and escape is difficult if even possible. The probability of a serious fire event occurring in a given space mission is very low. On a long-term basis, this probability is significant, for certain breakdowns that can lead to the onset of fire are by no means rare. Among these are electrical and heating overloads, spills and resulting aerosols, energetic experiment failures, and ignition of accumulated wastes or trash (1). For human-crew spacecraft, fire prevention is promoted by the use of materials and assemblies that are classified and selected by their fire resistance (2). This selection is determined through tests that are derived, to some extent, from those used in other modes of transportation, particularly aircraft. Spacecraft materials, however, must meet standards of maximum flame-spread distance (self-extinguishment) following ignition, rather than maximum heat release. These criteria ensure that breakdowns and ignition events will not lead to fires that threaten damage, loss, or injury (3), although even minor events may cause subsequent damage, such as corrosion of electronic components. A large database of acceptable materials and components has been compiled in the past two decades through testing conducted in ground laboratories, under "worst-case" conditions, where flame propagation is promoted by buoyancy.

Fire prevention in spacecraft must consider the unique characteristics of fire behavior in the non-convective, low-gravity (microgravity) environment of Earth-orbiting, planetary-transit, or surface-habitat enclosures (4). Flammability and flame spread in space are not subject to natural-convection buoyancy, but they are sensitive to low-level forced convection (atmospheric ventilation flows) and oxygen concentration. This paper discusses the knowledge of fire in low gravity, as well as the current and proposed methods for the selection of fire-resistant articles. In practice, reliance on fire prevention is supplemented in the complete program of spacecraft fire safety by configuration controls and the fire intervention steps of detection and suppression. In addition, a vigorous research and technology program is in process to identify hazards, improve test methods, and validate policies and practices (5).

2. FIRE EXPERIENCE IN SPACE

Fire and explosion disasters have occurred in ground testing and launch operations. In contrast, internal fires in spacecraft are very rare, but a few events have been serious enough to reinforce the fear of fire hazards in spacecraft operations.

In the outbound segment of the 1970 Apollo 13 mission to the Moon, an electrical short circuit in the pressurized oxygen tank started a fire that caused the tank to explode, damaging other critical systems. Fortunately, through the ingenuity of the crew and the ground Mission Control, the crew was able to use the supplies in the lunar module, along with other improvisations, to return to Earth safely (6).

A fire event in 1997 on the Russian orbital station Mir fortunately caused little damage and no injury, but it threatened to create a catastrophe. A solid-fuel oxygen generator for supplementary use caught fire and produced a "blow-torch-like" flame that burned the generator housing and produced thick black smoke spreading quickly throughout the station (7,8). The crew tried to contain the fire by applying the contents of several aqueous-foam extinguishers, but no doubt the fire extinguished only when the generated oxygen was depleted. Informal reports also confirm that, in the period of over ten years of Mir operations, several other small fires have occurred, but documentation of these incidents is sketchy.

Five fire-threatening incidents involving component overheating or electrical short circuits have also been reported in the nearly 100 missions of the Shuttle Transportation System, which cover a period of 20 years of operation (9). In these incidents, the crew detected the problem immediately and prevented a possible fire by removal of power, without the need for extinguishers (3). About 15 other anomalies, such as false alarms or failures of the built-in test circuits of the smoke detectors, have also been recorded in Shuttle operations. The probability of such incidents may increase in the future, with the coming of longer and more complex orbital-station (the International Space Station) and extraterrestrial missions.

3. FIRE CHARACTERISTICS IN EARTH–ORBITING AND EXTRATERRESTRIAL ENVIRONMENTS

3.1 Brief Introduction to Research. Fire prevention and response in spacecraft obviously benefit from fundamental and applied research on combustion in low gravity (microgravity). Theoretical analyses of combustion in non-buoyant environments are common, but experimental verifications, necessary for fire-safety applications, are not easy to obtain (10). Opportunities for flight tests on the Shuttle and space stations are quite limited. Most experimental microgravity combustion studies to date have been conducted in ground-based facilities. The principal venues are the two free-fall drop towers at the NASA Glenn Research Center, which provide 2.2 and 5.2 sec each of microgravity conditions of the order of 10^{-4} g, where g is the sea-level acceleration of 9.8 m/s^2 (11). Other facilities are aircraft flying parabolic (Keplerian) trajectories, which allow up to 20 sec of low-gravity time, at significantly higher residual-gravity levels in the range of 10^{-2} g. Sounding rockets can increase the low-gravity exposures to 5 to 15 min or longer at residual gravity levels of the order of 10^{-4} g.

The first fire-safety related microgravity combustion experiments were performed in 1966 aboard a KC-135 aircraft laboratory (12). Ignition susceptibility was found to be similar to that in normal gravity, but combustion was suppressed in microgravity, in terms of reduced rates of flame spread. Drop-tower experiments on various materials found similar suppression in microgravity, although the differences diminished for very thin fuels (13). The first set of combustion experiments conducted in an orbiting spacecraft were those of Kimzey in 1974 on the Skylab space station (14). These experiments on the ignition, flame spread, and extinguishment of common materials in an enriched-oxygen environment also noted the reduced flammability in microgravity.

These early findings led to the plausible conclusion that normal-gravity flammability assessments provide a large margin of safety for low-gravity service. Recent theoretical and experimental results indicate, however, that microgravity combustion is extremely sensitive to atmospheric flow and composition. Under some conditions, material flammability may be comparable to, if not greater than, that in normal gravity. A brief summary of the current understanding of flammability behavior in spacecraft and extraterrestrial environments follows.

3.2 Effects of Oxygen Concentration on Material Flammability in Low Gravity. Virtually quiescent environments are achievable only in microgravity, an environment in which the appreciable buoyant flow always present in normal-gravity flames is absent. Early studies on the combustion of thin-paper fuels under various oxygen concentrations in quiescent microgravity show that, for atmospheres with high oxygen concentrations, the flame-spread rate is independent of the gravity level (15). For oxygen concentrations below about 30 to 40%, however, the flame-spread rate for the paper fuels is lower in microgravity than in normal gravity (Fig. 1). Furthermore, the minimum oxygen concentration in which a flame will self-propagate is higher in microgravity than in normal gravity (*i.e.*, the flammability range is reduced), as also illustrated in Fig. 1.

In order to study thicker solid materials, longer exposure times in microgravity than are available in ground-based facilities are necessary. Opportunities for tests in Earth orbit resumed on the Shuttle starting in 1990, with the test series called the Solid Surface Combustion Experiment (SSCE). A total of ten SSCE campaigns (each contributing essentially one or two data points) have furnished information on the combustion of ash-free filter paper (16) or polymethylmethacrylate (PMMA) samples (17) in quiescent microgravity environments. The tests determined the effects of gravity, oxygen concentration, and pressure on the burning process. Analysis of the combustion of thin fuels shows that the flame-spread rate increases with pressure in quiescent microgravity, which is quite different from the behavior in downward spread in normal gravity. The SSCE experimental results are accurately predicted by a theoretical model that includes gas-phase radiation.

3.3 Effects of Opposed-Flow Flame Spread Across Solid Surfaces. Flow-aided flame spread from a central ignition point over thermally thin (essentially isothermal) cellulose fuel samples was studied in the Radiative Ignition and Transition to Flame Spread (RITSI) experiment, conducted on the STS-75 Shuttle mission in 1996 and in three campaigns in a 10-sec Japanese drop tower (18). In RITSI, a rectangular sheet of paper is ignited at the center by a focused beam from a tungsten/-halogen lamp with superimposed flow of a nitrogen-oxygen mixture at speeds of 0 to 6.5 cm/s. The ignited sample propagates a flame under all conditions studied, except at the lowest oxygen concentration of 21 percent with zero flow. In all other cases, the flame spreads in a fan-shaped pattern in the upstream direction (towards the flow), as shown in the photograph in Fig. 2. The fan angle increases with increasing external flow and oxygen concentration. Downstream flame spread (the expected result in normal gravity) is observed only after the upstream flame spread is complete. This is due to the depletion of oxygen by the upstream flame, called an "oxygen shadow" by the RITSI investigators. Linear relationships between imposed flow and concurrent (downstream) flame-spread rate, and non-monotonic relationships between the imposed flow and opposed (upstream) flame-spread rate are determined from the experiments (18).

Opposed-flow flame spread over thermally thick (essentially adiabatic) fuels was studied in sounding-rocket experiments, Diffusive and Radiative Transport in Fires (DARTFire), conducted in four test campaigns since 1996 (19). Experiments on 6.35-mm-thick black PMMA samples in atmospheres with 50- and 70-percent oxygen concentrations indicate that, at low values of opposed flow velocity, flame-spread rate increases with velocity to about the 0.5 power. Stable flames exist in microgravity under atmospheric flows with speeds as low as 1 cm/s.

3.4 Effects of Concurrent-Flow Flame Spread Across Solid Surfaces. Upward flame spread over solid fuels was studied by the Forced Flow Flame Spreading Test on the STS-75 Shuttle mission in 1996 to clarify the mechanisms of flame spread and extinction, as influenced by concurrent atmospheric flow (20). Tests in a miniature combustion tunnel examined the effects of flow speed and fuel thickness for flat paper fuels, and flow speed, flow direction, and initial fuel temperature for cylindrical molded-cellulose fuels. Within the flow-velocity limits set by the dimensional constraints of the apparatus, observed flame lengths agree well with theoretical predictions. The axisymmetric geometry of cylindrical fuels permit simplified modeling. Their results indicate that flame length increases with increasing air velocity and preheat temperature (75 to 135 °C).

A similar combustion-tunnel test, conducted on Mir in 1998, observed the concurrent-flow flame spread along 4.5-mm-diameter cylindrical samples of three plastic materials: high-density polyethylene, PMMA, and Delrin (8). These tests were conducted in near-"air" atmospheres, ranging from 23- to 25-percent-oxygen concentration. The results indicate that each material has a characterizing limiting-combustion velocity in air, that is, a minimum concurrent air flow necessary to maintain flame spread in microgravity. For the three plastic materials tested in Mir, the limiting combustion velocity is very low, less than 1 cm/s. The limiting combustion velocity decreases further toward zero as the atmospheric oxygen concentration increases.

Researchers can predict the limiting-combustion velocity from a balance of the total required oxygen to that supplied through molecular diffusion (21). Representative results are shown in Fig. 3, which presents the theoretical limiting-combustion velocities for the three plastics tested in the cited Mir study. Flammable conditions are to the right of each curve. The shaded band indicates the range of atmospheric oxygen concentrations expected in spacecraft operations, including those experienced in the Mir tests. The experimental results of burn/no-burn boundaries are generally consistent with the analyses, although the small velocity differences of 0.1–0.2 cm/s are below the order of experimental velocity-control resolution.

3.5 Effects of Material Properties on Low-Gravity Flammability. Only a limited variety of reference materials have been burned experimentally in a microgravity environment. The tested materials are selected for scientific expedience rather than practical material-usage criteria; hence, these materials are strongly flammable rather than fire-resistant.

Thermally-thin cellulose fuels provide the most comprehensive database of material flammability characteristics from testing in both short-time ground-based facilities and in spaceflight accommodations. These fuels, in the form of various paper products, are found in large quantities in all human-crew space missions, since there are no satisfactory substitutes. Configuration control, which is frequently used to reduce the fire potential of flammable materials, is logistically impossible to implement for all notebooks, data files, and so on. A possible added fire hazard for cellulose is cracking and curling during flame spread, which can lead to break-off of burning pieces to be carried by weak ventilation to adjacent flammable materials as an ignition hazard. In addition, cellulose may partially degrade during flame spread leaving a hot and highly reactive char that smolders. Smoldering can persist long after apparent flame spread ceases (22).

For thermally-thick materials, few low-gravity tests have been conducted, since space flight is required for the relatively long times of flame initiation and spread. The polymeric materials tested to date all exhibit melting or glass transition at temperatures below the pyrolysis temperatures, which strongly affects the combustion behavior of the materials. On-orbit materials tested include PMMA, nylon, Delrin, silicone rubber, plastic wire insulation, candle wax, and high- and low-density polyethylene (HDPE, LDPE). PMMA is found to develop a thick molten layer with significant in-depth thermal degradation, which causes bubbles that reach the molten surface and escape as burning fuel-vapor jets (8). Nylon is observed to produce significant flame jets that provide a source of flow in the otherwise quiescent environment (14). Delrin also develops a molten bubble layer that expands almost as a foam, with extremely large flaming jets from the surface (8). Possibly due to its high oxygen content, Delrin burns with a nearly invisible blue flame. HDPE develops a thick molten layer, but it does not produce significant vapor jetting. LDPE-coated wire forms a liquid ball of low-viscosity molten polyethylene wetting the wire in low gravity (23).

Porous polymer foams have been studied both in smoldering tests in spaceflight and flaming tests in ground-based facilities. Polyurethane-foam smoldering experiments have shown that, for small enclosed samples, in the absence of any flow through the foam, smoldering is not sustained. However, a bulk flow as low as 1 mm/s through the foam is adequate to maintain the smoldering (24). Flaming tests with polystyrene foams show that melting of the foam is significant, and flame spread over foams is very rapid compared to that over higher-density materials (25). This suggests that a surface treatment, or covering, may be an effective deterrent to flammability of foam materials in microgravity.

4. MATERIAL SELECTION FOR FIRE PREVENTION

4.1 Ignition and Oxygen Controls. Fire prevention implies the elimination or reduction of one or more of the elements of the familiar fire triangle of fuel, ignition source, and oxygen. The principal thrust in spacecraft fire prevention is fuel reduction through material selection. Ignition sources are minimized through the usual practices of electrical bonding and grounding, electrical and thermal overload protection, working-pressure relief settings, and highly conservative wire and cable current ratings.

Oxygen control is also recognized. Cabin atmospheres in the U.S space program have evolved from the 100-percent oxygen, 24-kPa Apollo atmosphere, through the 65-percent oxygen, 37-kPa Skylab atmosphere, to the current Shuttle and ISS sea-level air atmospheres. This life-supporting but flame-promoting air atmosphere will continue to be the standard for future human-crew space missions, although preconditioning prior to extravehicular activities requires 30-percent oxygen at 70-kPa total pressure. Future adjustments of the spacecraft atmosphere for safety must consider the overriding needs to limit maximum total pressure for structural constraints and to maintain a near sea-level air atmosphere relative to ground reference conditions for medical and biological research (2).

4.2 Material Testing and Standards for the Shuttle. The requirements and standards for the National Space Transportation System (STS, the Shuttle) assure the safe operation of the STS and its payloads by controlling hazards associated with each payload individually and in combination. The first standard developed for the NSTS was NASA Handbook (NHB) 1700.7 "Safety Policy and Requirements for Payloads Using the STS, Dec. 1980." From this document, all necessary Shuttle technical and system-safety requirements are derived. As a result of the STS-51L Challenger disaster in 1986, this document underwent an extensive revision reflecting increased safety awareness, and it was then released as NSTS 1700.7 (26).

NSTS 1700.7 is written for user organizations to identify and control hazards associated with each payload. Payload hazards that are controlled by compliance with specific requirements of NSTS 1700.7, other than failure tolerance, are called "Design for Minimum Risk." Fire is an example of this type of hazard. Each payload must be assessed to assure that it will not cause an uncontrolled fire within the Shuttle Transportation System or its associated payloads. The use of safe materials for flight is assessed in Section 209 "Materials" of NSTS 1700.7. Additional requirements, including oxygen concentration and atmospheric pressure for the various payload locations, are found in Paragraph 209.2 "Flammable Materials."

The guideline used to make the flammability assessment for flight acceptance is NSTS 22648, "Flammability Configuration Analysis for Spacecraft Applications," Oct. 1988 (27). Figure 4 is the flammability assessment logic diagram found in NSTS 22648 that is used to determine if a configuration is acceptable or if it requires flammability testing per NASA-STD-6001 (28). The flammability assessment is provided as a hazard control and documented in NSTS/ISS 13830 Rev C "Payload Safety Review and Data Submittal Requirements, July 1998."

4.3 Material Testing and Standards for the ISS. An Addendum was created to incorporate the International Space Station (ISS)-specific requirements utilizing the NSTS 1700.7 document (29). The ISS Addendum requirements are per paragraph 209.2b "Other Habitable Area". In addition to the original paragraph, the addendum requires the following:

- The ISS worst-case operating environment is [105 kPa] with 24.1 percent oxygen for all locations except airlocks. Airlock worst-case environment is [70.3 kPa] with 30 percent oxygen. Payloads are only required to test materials in the worst-case airlock environment if [intended] to operate in the airlock during EVA (extravehicular activity by the flight crew) preparations.

Material test methods and standards for the ISS modules and payloads are, at this time, identical to those of the Shuttle. A separate set of requirements has been derived, however, for the fire detection and suppression subsystem of the life-support system (30). With the exception of those of the Russians, material-acceptance standards of the U.S. and its international partners are identical. Russia has developed an independent material database. Russian flammability standards are, in general, as strict as those of the other partners in the ISS (31).

The long-term and complex missions of the ISS, and future extraterrestrial missions, may also introduce new problems to be addressed in material control. Aging and continued usage of materials and components may alter their fire resistance. Paper and other wastes can accumulate in quantity.

With time, crew members may become careless or forgetful in following prescribed containment procedures of waivered articles. Replacement crews may be unaware of the location of flammable articles.

4.5 Description of Specific Fire-Resistance Tests. For U.S. spacecraft, fire-resistant items are selected through testing standards defined in the NASA STD-6001 (28). The tests and standards are unique to spacecraft requirements, although some are derived from methods in common use for aircraft and ground transportation. Table 1 summarizes the principal flammability tests.

Table 1.—Selected Flammability Tests for Articles in NASA Human-Crew Space Missions.

Test No.	Application	Title (Reference ASTM Test)
1	Sheets, coatings, foams, insulated wires	Upward Flame Propagation
2	Sheets, coatings, foams that fail to meet the criteria of Test 1; also major-use nonmetals with greater than 0.37-m^2 exposure	Heat and Visible Smoke Release Rates (Oxygen Consumption (Cone) Calorimeter, ASTM E-1354)
3	Liquids, coatings	Flash Point of Liquids (Pensky-Martens Closed Tester, ASTM D-93)
4	Insulated wires	Electrical Wire Insulation Flammability
8	Containers	Flammability Test for Materials in Vented or Sealed Containers
17	Metals, nonmetals for oxygen service	Upward Flammability of Materials in Gaseous Oxygen

The test of widest application is Test 1, which has been in use for over 25 years with minor upgrading. The performance criterion of Test 1 is the self-extinguishment of a 30-cm-long by 5-cm-wide sample, mounted vertically and ignited chemically at the bottom, before any resulting flame progresses for a distance of 15 cm or beyond (shown as the limiting flame-spread height in Fig. 5). As will be shown, the test setup can also accommodate some bulk articles as well as sheet materials. In addition to the self-extinguishment criterion, an acceptable item must not ignite a sheet of K10 paper mounted horizontally 20 cm below the sample holder. Fire resistance is determined within a closed chamber at the worst-case-use oxygen concentration and pressure environment.

Test 4, illustrated in Fig. 6, is an adaptation of Test 1 to evaluate the fire resistance of wires or wire bundles under electrical loads. A 31-cm length of wire is mounted at an angle of 15° from the vertical, a position found to give less interference from combustion products or flow of molten insulation than vertical mounting (32). If wire bundles are to be tested, six non-connected wires are cut and laced to the active conductor. The current-carrying wire is preheated by direct current to an initial temperature of 125 °C, or to the maximum operating temperature of the wire, for five minutes. Then, the wire is ignited by a chemical igniter or by increasing the internal heating current. The criteria of maximum burn length (visible insulation consumption) prior to self-extinguishment and non-ignition of a paper sheet by hot particles are the same as for Test 1. Test 2 determines the ignitability, maximum and average rate of heat release, and amount of smoke obscuration in a standard apparatus (the cone calorimeter) that preheats the samples under a controlled atmosphere by an external heat flux from a conical heater (33). The samples are ignited by a spark plug, if they do not self-ignite upon preheating. Test 2 is required for major-use nonmetallic panels and as an option for the retest of the flammability of sheet or panel samples failing Test 1.

For European spacecraft, fire-resistant items are selected generally through the same testing methods and performance standards prescribed for U.S. spacecraft, with the addition of a limiting-oxygen-index test (ASTM D 2863-97) for sheet plastic materials (34). This test determines downward flame propagation, in contrast to the upward propagation of NASA Test 1; but, in most cases, the acceptability of items determined by either the criterion of oxygen index or that of upward flame propagation is the same (35).

Upward-flammability assessment offers several advantages in the screening of materials. The NASA Test 1 simulates the beginning of a fire with an ignition flux of typically 75 kW/m^2 maintained for 25 sec (36). It is a severe "worst-case" test in terms of ignition energy, means of edge ignition, direction of buoyancy-assisted flame spread, sample thickness, and oxygen concentration. Nevertheless, the test models a fire scenario that has no counterpart in low gravity. In fact, all practical spacecraft flammability testing, as well as performance and calibration testing of fire-detection and suppression technology, is of necessity conducted on the ground, at normal gravity, not in the environment of the orbiting spacecraft. Still, the use of ground-based test methods and criteria has provided an extensive database of thousands of qualified articles that greatly contribute to the overall strategy of spacecraft fire safety.

5. PROGRESS IN MATERIAL SELECTION FOR SPACECRAFT

5.1 Experience and Database of Materials. The MSFC-HDBK-527/JSC 09604, Materials Selection List for Space Hardware Systems and the Materials and Processes Technical Information Systems (MAPTIS), an electronic version of the "Handbook", are used to select and assess materials for flight payloads. The database contains listings for materials that have been tested in accordance with NASA-STD-6001 Test 1 or other tests and given a flight rating (Table 2). The ratings listed in the database do not imply in themselves an acceptance or rejection of the article, Instead, the decision for use is based on the specific application and suitability of an item in the spacecraft-use environment.

Table 2.—Rating Explanations for Flammability Test Results by NASA STD-6001 Test 1.

Rating	Qualification
A	Materials with sample measurements and test conditions as recommended in Test 1: • Burn length of 15 cm (6 in.) or less, • No drip burning or small drip burning, and • No ignition of K10 paper. Standard test is three samples. (The test can fail, but not pass, on less than 3 samples.) Configuration test can be rated on one, two or three samples
B	Materials that have a burn length of more than 15 cm (6 in.) but less than 30 cm (12 in.) in Test 1, with: • No drip burning or small drip burning, and • No ignition of K10 paper. Standard test is three samples. (The test can fail, but not pass, on less than 3 samples.) Configuration test can be rated on one, two or three samples.
C	Materials that burn totally with no drip burning, or small drip burning, with no ignition of K10 paper.
X	Materials ignite K10 paper with small, moderate or large drip burning. The burn length is not a factor.
S	Special test conducted on materials
I	Less than 3 standard samples with less than 30 cm (12 in.) burn length. No drip burning or no ignition of K10 paper with small drip burning.
U	Unacceptable data

MAPTIS is an electronic database accessible via two methods. First, MAPTIS is available through the Internet at http://map1.msfc.nasa.gov/WWW_Root/html/page7.html. This contains flammability data most recently tested. No password is required to access the data. Second, a more extensive electronic database can be accessed through *Telnet*, but it requires an access password and training. There is a form available on the Internet site to apply for a password. The MAPTIS database is maintained at the NASA Marshall Space Flight Center (MSFC), Huntsville, AL.

For items that are not listed in any of the materials selection guides, testing is required. Testing is accomplished by submitting a test request form to MSFC or to NASA Johnson White Sands Test Facility (Las Cruces, NM). When the tests are completed, a report is returned with information indicating if the item is acceptable for flight.

Figure 7 is a set of photographs illustrating the results of qualifying tests for a common component, a small plastic-body motor and fan used in some space experiment packages (18). The article and the Test 1 setup are shown in Figs. 7(a) and (b). The results of one test in an atmosphere of 24-percent oxygen are shown in Fig. 7(c); this performance merited a rating of C. The debris remaining after another sample of the same article was tested in an atmosphere of 30-percent oxygen is shown in Fig. 7(d); this obviously received an X rating.

Many items cannot qualify with the desired ratings, yet they are necessary in the spacecraft inventory. Common examples are paper, cotton clothing and towels, data films, and "off-the-shelf" components, like the fan shown in Fig. 7. Acceptance of these articles is through documentation and waivers. The fire risk of these items is reduced through control of spacing, elimination of fire-propagation paths, and storage in nonflammable containers or under non-flammable covers (27).

5.2 Research on Material Flammability Testing in Low Gravity. Several forced-air combustion-tunnel apparatuses have been developed for material-flammability testing in microgravity with imposed atmospheric flows. The DARTFire project, cited earlier, has an apparatus that incorporates imposed flow, atmospheric control, and radiant heat flux as variables in flammability measurements (19). Experiments select flux levels to offset approximately either the surface radiative loss alone (of the order of 5-10 kW/m^2) or the surface plus flame radiative loss (20 kW/m^2). Results confirm the strong influence of velocity on flame spread, although the tests were conducted, for fundamental understanding, at oxygen concentrations considerably higher (50 to 70%) than those in current human-crew spacecraft atmospheres.

The Lateral Ignition and Flame Spread Test (LIFT, ASTM E-1321) is a standard method of measuring ignition-delay and flame-spread characteristics of materials (37). The LIFT apparatus, however, relies on gravity for the transport of heat and mass, and consequently cannot be used in microgravity. A flammability-test apparatus, Forced Ignition and Spread Tests (FIST), is now in development as a test bed that duplicates the ambient conditions in space-based environments (38). FIST tests will provide information about the ignition delay and the flame-spread rate of sheet materials as functions of externally applied radiant flux, oxidizer velocity, and oxygen concentration.

5.3 Unique Hazards in Microgravity. Research analyses and experiments have revealed a number of peculiarities in pyrolysis or fire processes in low gravity. Some of these characteristics can be directly related to possible fire hazards in spacecraft operations. For example, spills or line breaks can create aerosols or particle clouds that are highly flammable in any gravitational environment. In normal gravity, these heterogeneous mixtures settle or disperse rapidly. In low gravity, however, they can persist for long time periods, increasing the opportunity for exposure to ignition sources. Recent studies also show that the particle arrays may have greater peak explosion pressures in microgravity compared to normal gravity, due to the uniform and stable composition of the aerosols in low gravity (39).

Effervescing or easily vaporized materials tend to eject hot bubbles or droplets when ignited. These globules can drip harmlessly in normal gravity, but they propel radially as potential ignition sources in low gravity. This phenomenon has been observed in the burning of nylon Velcro strips (40), plastic cylinders (41), and wire insulations (23).

The burning rate of metal wires in oxygen is greater in low gravity than in normal gravity, due to the compact flame zone, created by the retention of molten fuel on the wire without dripping as in normal gravity (42).

Smoldering can initiate in concealed volumes. While the flame spread is slow and heat release is low, tests in microgravity indicate that smoldering can persist for long periods, producing toxic gases and threatening eventual transition to rapid flaming or ignition of adjacent surfaces (24).

6. CONCLUDING REMARKS

This paper surveys the methods and experience in the selection of fire-resistant items for spacecraft use. All acceptance testing for space must be performed on the ground, with the articles subjected to a strong upward buoyant flow. The tests assume that items resisting flame spread under this severe condition will be equally resistant in the space environment, where this upward flame-promoting flow is absent. Experimental and modeling research, however, shows that very low flows, of the order of ventilation velocities, can stimulate low-gravity flames to more than compensate for the lack of buoyant flow. On the other hand, if the ventilation flow can be stopped (as a first-order fire response, for example), the low-gravity fire propagates very slowly, if at all, under air environments.

Certainly, the large database of acceptable fire-resistant materials compiled in years of testing is still essential to fire prevention in spacecraft. Almost all of these acceptable database items should resist flame spread in microgravity except under unusual circumstances. More important is the fact that the database of fire-resistant items is only one feature of a complete fire-safety strategy, which includes configuration controls, ignition-source prevention, and fire detection and suppression.

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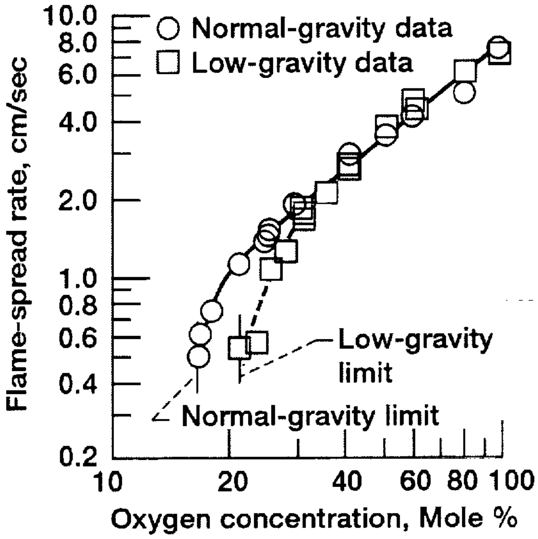

Figure 1.—Experimental data on flame-spread rates and flammability limits of thin-paper fuels for downward normal gravity and quiescent microgravity.

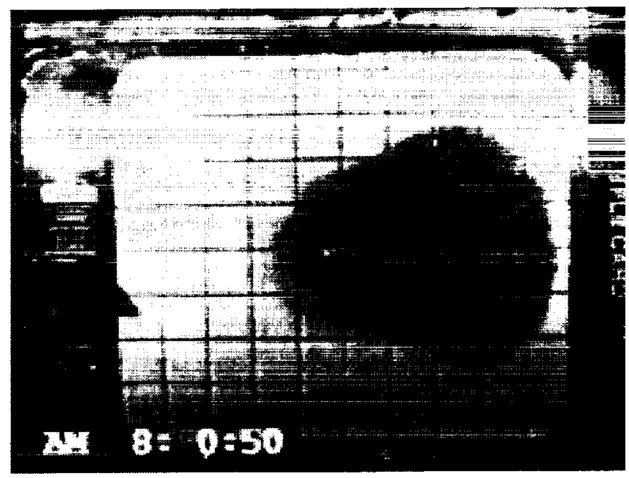

Figure 2.—Flame spreading into the air flow for centrally ignited filter-paper sheet in microgravity. Air flow is from right to left.

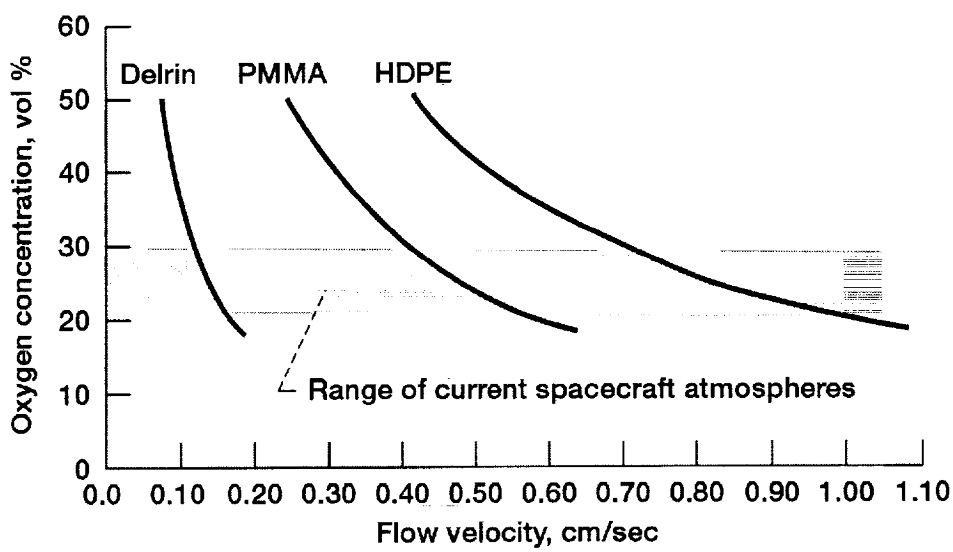

Figure 3.—Theoretical limiting flow velocity for ventilation flow opposed to flame spread in microgravity for three plastic materials.

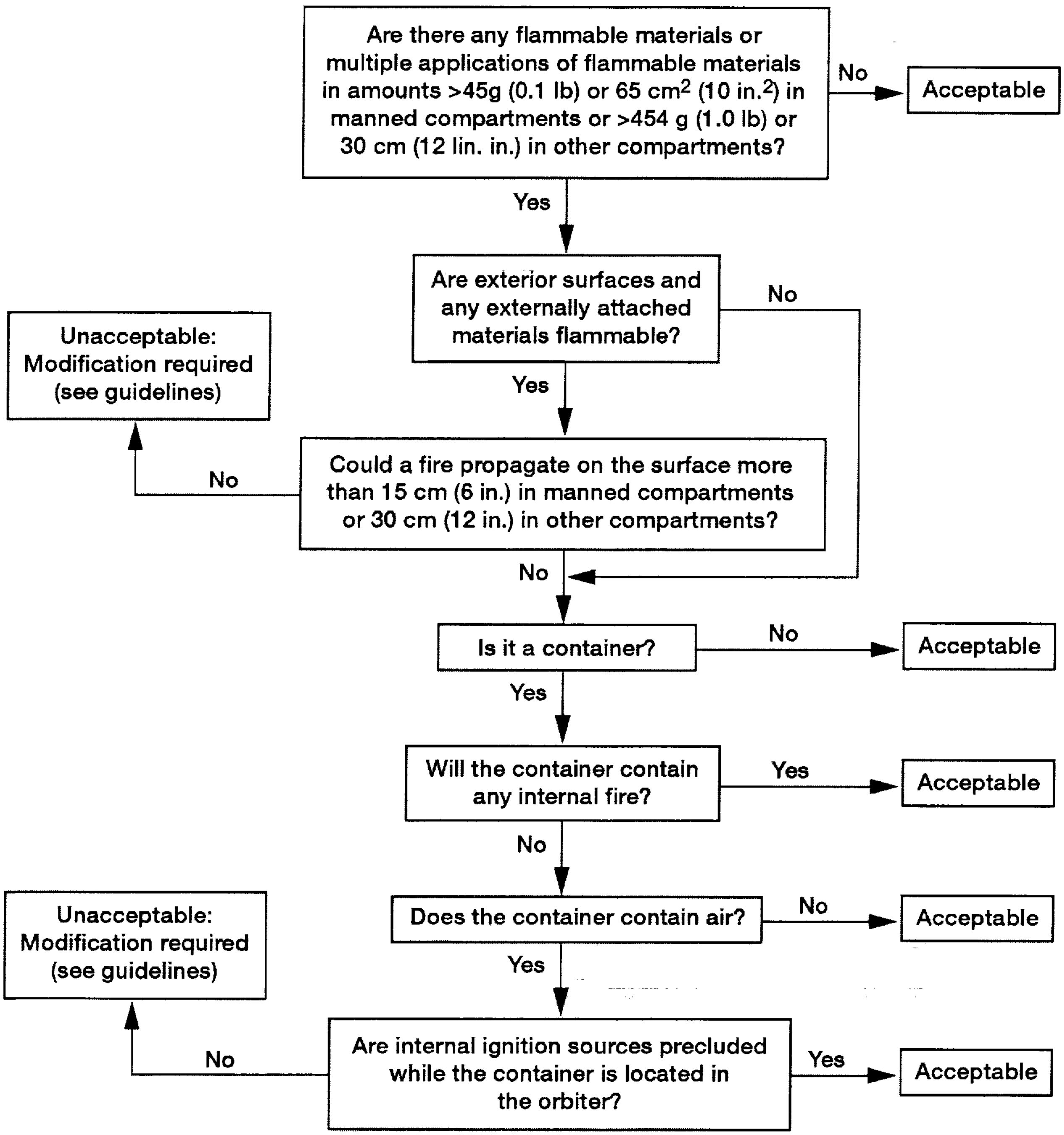

Figure 4.—Flammability assessment logic diagram.

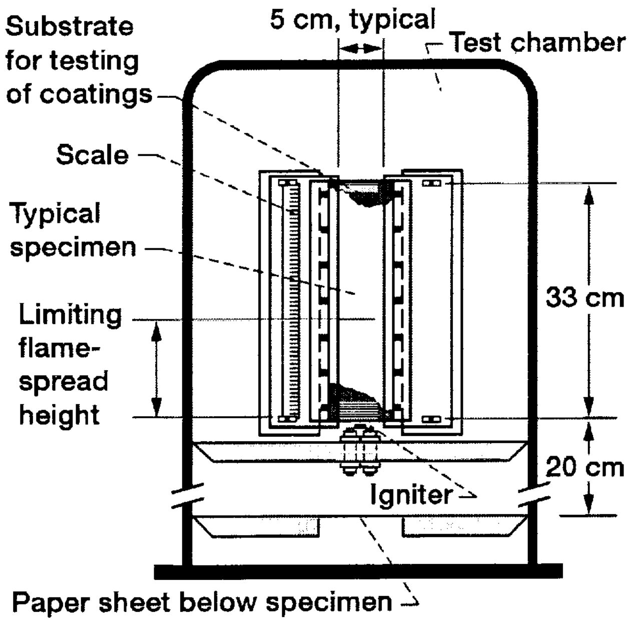

Figure 5.—Sketch of apparatus for NASA STD-6001 Test 1, upward flammability test.

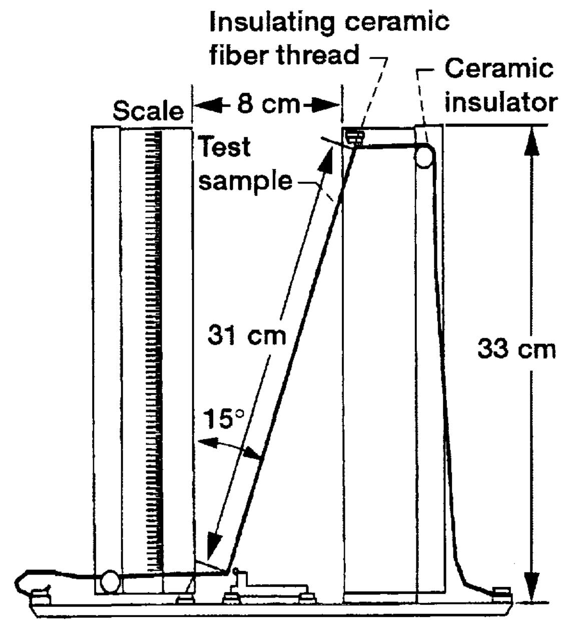

Figure 6.—Sketch of apparatus for NASA STD-6001 Test 4, electrical wire flammability test.

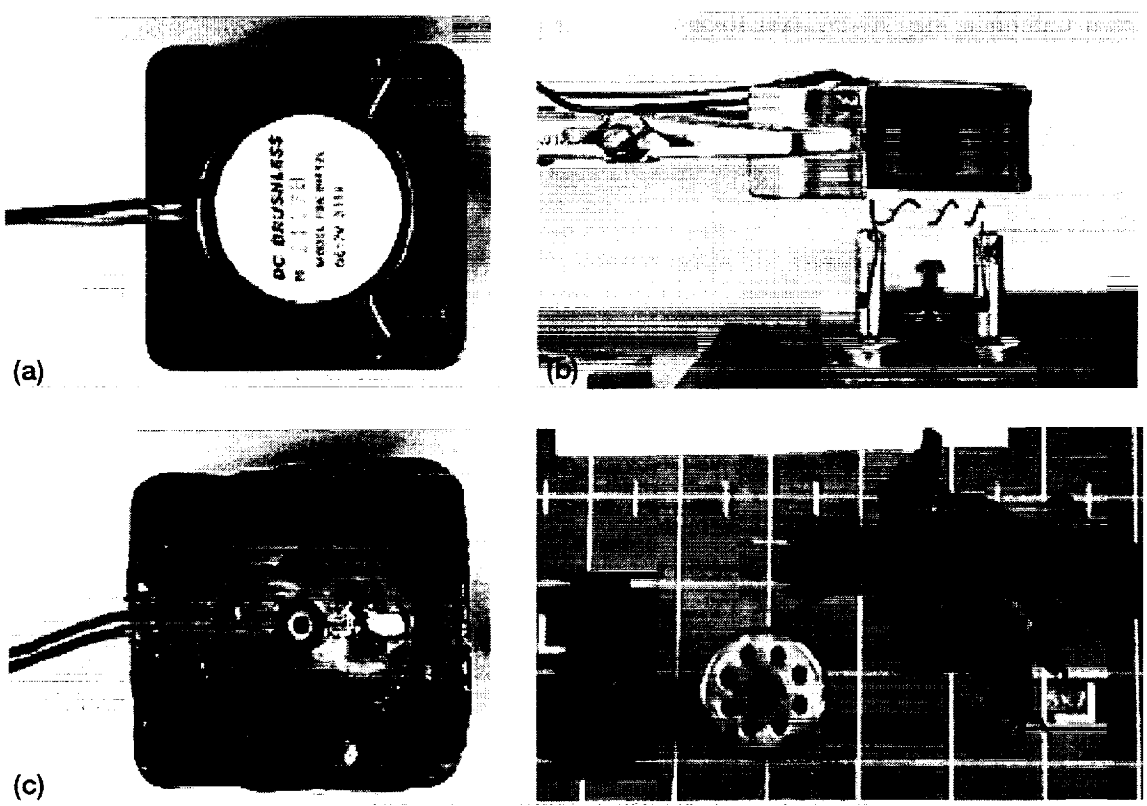

Figure 7.—Example of NASA 6001 upward flammability tests on 8 x 8 x 2.5-cm thick plastic motor and fan samples. (a) Article prior to testing. (b) Test setup, with article horizontal and igniter under case. (c) After testing at 24.6% oxygen. (d) After testing at 30.3% oxygen.

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13. ABSTRACT ***(Maximum 200 words)***

Spacecraft fire-safety strategy emphasizes prevention, mostly through the selection of onboard items classified according to their fire resistance. The principal NASA acceptance tests described in this paper assess the flammability of materials and components under "worst-case" normal-gravity conditions of upward flame spread in controlled-oxygen atmospheres. Tests conducted on the ground, however, cannot duplicate the unique fire characteristics in the nonbuoyant low-gravity environment of orbiting spacecraft. Research shows that flammability and fire-spread rates in low gravity are sensitive to forced convection (ventilation flows) and atmospheric-oxygen concentration. These research results are helping to define new material-screening test methods that will better evaluate material performance in spacecraft.

14. SUBJECT TERMS

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