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Fire Safety Concerns in Space Operations

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FIRE SAFETY CONCERNS IN SPACE OPERATIONS*

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ABSTRACT

While fire safety has always had major attention in the planning and conduct of spacecraft operations, the approach to a permanent orbiting facility, the Space Station, will place even greater demands on fire prevention and control. On the one hand, the long duration and complexity of this project calls for more stringent fire safety measures. On the other hand, the importance of making the Space Station accessible to a variety of users calls for simplified and flexible fire controls. The paper reviews the state-of-the-art in fire safety, describing the fundamentals of microgravity combustion and the applications to fire detection, fire extinguishment, material assessment, and spacecraft atmospheres. Future needs in research, technology, and standards are identified. These include a better understanding of microgravity combustion, novel fire control technology, and use of methods derived from aircraft and undersea experience.

INTRODUCTION

This paper discusses the state-of-the-art in fire control techniques and identifies important issues for continuing research, technology, and standards. The historic approaches to fire safety in the U.S. space program has already been reviewed briefly by the author (Ref. 1). The growth of space activities produced more complex hardware and missions, and the need for fire safety protection grew accordingly. Whereas Mercury, Gemini, and Apollo relied on the spacecrew to monitor potential fire hazards, the Shuttle incorporates smoke detectors, plus fixed and portable fire extinguishers (Ref. 2). Material assessments have likewise grown from simple flammability criteria to a set of material test codes and alternatives, chief of which is the NASA Handbook NHB 8060.1B, a document subject to periodic revision (Ref. 3). The Space Station, a permanently-inhabited low earth-orbit facility imposes new demands on fire safety (Refs. 4 and 5). The Space Station will accommodate a crew of various skills engaged in construction and maintenance, scientific experiments, and commercial technology development. Crew activities will include periods of ordinary living, housekeeping, and recreation. The Space Station must serve as a self-contained community since rescue is many days away. Thus, the Space Station may call for improved and innovative fire safety strategies, as compared to previous space flight programs. It is important, however, to make the Space Station as accessible as possible to a variety of users. To meet these conflicting needs, fire safety measures must strive for simplicity, flexibility, generalization, and cost effectiveness, without compromising human or structural safety criteria.

What is sought in safety analyses is the minimization of risk or potential for harm. The ideal safety model would yield a zero probability of any damage or injury in the spacecraft. A practical or baseline goal, however, is a slight but finite probability of damage or injury, limited to an occurrence that would not impede the spacecraft operation (Ref. 6). This criterion applied to fire safety can be interpreted in terms of the hazard review by Peercy et al. (Ref. 7). The first line of fire defense is "design to preclude", which implies that at all times two of the elements of the familiarity fire triangle (i.e., fuel, oxidant, and ignition source) are excluded. It is obvious that for the baseline safety goal for spacecraft this strategy is impractical; it is even undesirable, from the standpoint of user accessibility. Instead a second-order defense applies, "design to control". For fire safety, this strategy includes the usual fire safety elements of detection, extinguishment, material assessment, flammable material storage, compartmentalization, and so on.

This paper covers fire safety fundamentals (microgravity combustion) and the application of fire safety technology. The fundamentals review is an update of material presented to the JANNAF Safety and Environmental Protection Subcommittee (SEPS) in 1984 (Ref. 8). Fire safety technology, the essential ingredient of a fire control strategy, is reviewed in a discussion of current and future needs in fire detection, extinguishment, materials, and atmospheres in spacecraft. Much of this material is based on the findings of a 1986 Fire Safety Workshop held at the NASA Lewis Research Center (report in progress).

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FIRE IN THE SPACE ENVIRONMENT

As noted earlier, the simplified conditions for fire are the existence of the three elements of fuel, oxidant, and an ignition source. The combustion process usually takes place in the gas phase. The ignition and propagation of a fire involve the interplay of processes: these include the generation of gaseous fuel, fuel-air mixing, heat release from the combustion reaction, and heat transfer to adjacent material to generate additional gaseous fuel. These processes are described using energy, momentum, and mass transport equations. In normal gravity, the major distinguishing characteristic of this coupled system is the density-driven flow caused by the buoyancy of the rapidly-heated gases. In orbiting spacecraft, the net acceleration due to gravity is of the order of 10^{-6} times normal gravity, in this microgravity environment, buoyancy-induced flow is negligible.

MICROGRAVITY COMBUSTION EXPERIMENTS

It is not surprising that combustion research has shown great interest in the microgravity environment because this eliminates a major transport mechanism, exposing the subtle aspects of pressure, inertia, viscosity, and surface tension forces. Researchers have devised various experimental techniques to simulate microgravity. Buoyancy-induced flow can be reduced by simply balancing the densities of gaseous components, a method used to study flameless combustion (smoldering) in porous media (Ref. 9). The centrifuge is a familiar device to increase acceleration, and flame spread results as a function of increased gravity may be extrapolated in special cases toward a microgravity limit.

While the purpose of many microgravity combustion experiments has been the better understanding of combustion fundamentals, the applications to spacecraft fire safety have not been neglected. For fire-safety experiments, the most common microgravity simulation technique is free fall. Free-fall systems include drop tubes, in which fuel samples fall, and drop towers, in which complete experiment packages fall. Practical drop towers, of course, can rarely exceed a hundred meters in height, and thus they provide only a few seconds of free fall. For longer low-gravity exposure times of minutes, sounding rockets with data telemetry have been used. A practical compromise in test time against cost is in the use of an airplane flying a Keplerian or ballistic flight path. An airplane test facility provides microgravity exposures for up to 30 sec with the advantages of large experiment packages and the potential for attended testing.

Tests conducted in the two NASA Lewis drop towers have been the major source of microgravity combustion data pertinent to fire safety. The smaller of the two facilities, described in a report by Andracchio and Aydelott (Ref. 10), is a tower that provides 2.2 sec of free fall through a drop of 24 m. The experiment package is contained within a massive box that acts as a drag shield. Three spikes extending below the drag shield absorb the deceleration force upon falling into an aerated sand pit. The experiment package falls freely within the drag shield during the drop. The larger drop tower facility provides a free fall for 5.2 sec through a drop of 132 m. The 6.1-m-diameter shaft is evacuated to 13 Pa (100 μm of mercury) to eliminate the need for a drag shield around the experiment vehicle. A description of this facility and its application to fluid management research was described by Aydelott, et al. in a paper at the 1984 JANNAF SEPS meeting (Ref. 11). Reported gravitational accelerations in both facilities are of the order of 10^{-5} g. This is one to three orders of magnitude better than microgravities achieved in other facilities and flights.

The ideal facility for microgravity research is, of course, an orbiting spacecraft. One important fire safety test was the Skylab Experiment M-479 on Zero Gravity Flammability, conducted February 1974 and reported by Kimzey (Refs. 4 and 12). In these experiments, specimens of aluminized Mylar, Nylon, polyurethane foam, Teflon, and paper were ignited in a 65-percent-oxygen atmosphere. The study compared burning rates and the visual appearance of low-gravity flames to corresponding measurements in normal gravity. The extinguishment of flames by venting to the outside vacuum of space was also observed.

Reported studies from the NASA Lewis microgravity simulation facilities have covered those on combustion of premixed and diffusion-mixed gases, liquid droplets, and various solid samples of paper, plastics, and wire insulation. Experimental parameters have included the size and orientation of samples and the pressure and oxygen content of the atmosphere. Results were generally interpreted from high-speed visual and schlieren photography, with reference to corresponding normal-gravity results. Typical gaseous diffusion flames under normal gravity and microgravity are illustrated in the photographs of Fig. 1. The form of the microgravity flame is clearly different than that of the corresponding normal-gravity flame. The example shows an underventilated methane-air flame (limited diffusion of oxidant), which is elongated with a finite width at the flame tip. Such flames have been observed, on occasion, to grow and extinguish during the time period of the free-fall tests. For tests with other hydrocarbons or different fuel-flow rates, spherical overventilated microgravity flames have been observed (Ref. 13).

SPACECRAFT FIRE HAZARDS

The results of the microgravity combustion experiments have provided some understanding of where potential fire hazards may arise. In some respects, the spacecraft environment alleviates fire hazards; in other respects, it aggravates hazards. The state of knowledge applicable to microgravity fire safety is still primitive; and long-duration, larger-scale space experiments are clearly necessary for interpreting and predicting these effects.

A comparison of normal-gravity and microgravity combustion indicates that in some instances there is either no change or a reduction in the hazard of microgravity flames. Burning rates of most solid materials appear to be lower under microgravity unless forced-convection flows are present. The low gravity flames are more yellow and orange in color than corresponding normal-gravity flames, indicating that they are sootier and cooler. The flames show less "noise" and lower fluctuations than comparable normal-gravity flames, and, as noted earlier, under some conditions the flames may extinguish.

In contrast, there are other aspects of microgravity combustion that imply an increased level of fire hazards. Although the required energy to ignite practical materials remains the same as in normal gravity (Ref. 12), in microgravity, without convective heat losses, total incident energy may be reduced. Also, the absence of convection, for example, cannot be assumed in an inhabited spacecraft. While buoyancy or natural convection is not present, the spacecraft ventilating system provides forced convection, which may enhance low-gravity flame spread. Haggard investigated diffusion flames in the 2.2-sec drop tower with a diffusion flame tube surrounded by an air annulus (Ref. 14). Among the results were the findings that minimum air flows of 10 cm/sec could prevent methane flame extinguishment in microgravity.

Certain materials tend to melt, boil, and sputter when burning in microgravity. Globules of hot material, instead of falling to the floor, may drift to ignite adjacent surfaces. Kimzey (Ref. 12) observed this phenomenon with Nylon samples, and later Olson and Sotos confirmed this behavior studying Nylon Velcro (Ref. 15).

Microgravity flames, while cooler than corresponding normal-gravity flames, may be more radiant due to the concentration of soot particles. This could increase the dangers of flashovers and fire spread to adjacent surfaces through radiant heat transfer. Finally, flammable fuel-air mixtures caused by aerosols, sprays, spills, and dust accumulations may persist for long periods of time in microgravity, posing a serious fire hazard. Such particle clouds are also dangerous in normal gravity, but they tend to disperse rapidly through buoyancy or settling.

CURRENT MICROGRAVITY COMBUSTION RESEARCH

On-going microgravity research projects are still oriented toward the fundamental sciences of combustion processes. In a practical sense, however, these studies can contribute to spacecraft fire safety by establishing acceptable levels of material flammability and determining the ignitibility and extinction characteristics of flammable materials.

Two ground-based microgravity experiments are particularly relevant to spacecraft fire safety. One is the continuation of a series of solid specimen flammability studies. The current project, to be conducted in the NASA Lewis drop towers and Learjet airplane, will investigate microgravity combustion under low-speed forced flow. Thus the experimental, small-scale combustion tunnel duplicates the conditions of ventilation in a spacecraft. A second project is the analysis of and experiments on the microgravity combustion of porous materials, typical of foam cushions used in aircraft and spacecraft. Such materials are prone to smoldering, which is nonflaming combustion that may persist after apparent extinguishment.

Three combustion experiments planned for the Shuttle were described by Sacksteder at the 1984 JANNAF SEPS Workshop (Ref. 8). While the Challenger disaster has delayed the Shuttle flights and made the manifest dates uncertain, the recognized importance of the combustion experiments makes their rescheduling very likely. The experiments, illustrated in Figs. 2 to 4, are the Solid Surface Combustion Experiment (SSCE), the Particle Cloud Experiment Combustion (PCCE), and the Droplet Combustion Experiment (DCE). The SSCE (Fig. 2) provides a comparison of microgravity to normal-gravity flame spread that eventually may serve toward developing a standard flammability test for spacecraft material acceptance. The PCCE (Fig. 3) investigates the fire hazards of stable solid-air suspensions, a condition unique to microgravity. In the apparatus, each cylinder contains a mixture of suspended particulates, initially lycopodium powder (uniform diameter moss spores) and air. The physical arrangement of the experiment has had to address the problems of wall adhesion due to static charges, sealing of flow paths, and optical measurement techniques. The DCE (Fig. 4) is a more fundamental experiment, involving the burning of a freely floating droplet positioned by opposing retractable hypodermic needles, but it also promises eventual application to fire safety knowledge.

FIRE SAFETY TECHNOLOGY

The development of technology to preclude or control fire hazards in spacecraft arises in part from new applications of combustion science and in part from adaptation of existing ground and aircraft fire-control measures. This section describes the state-of-the-art and perceived needs in fire detection, extinguishment, materials assessment and atmospheric control.

FIRE DETECTION

Incipient fires can be identified by their signatures, or the changes in the environment from a "normal" condition. These signatures may include pressure rise, temperature rise, particle concentration, thermal or visible radiation, chemical species population, or combinations of these factors. The fire detector must be carefully positioned for effective transport of the signature information from the affected areas to the detector. It must also analyze the signature for appropriate action. Rapid and sensitive actuation of the sensor is critical, but this also implies increasing possibilities for a "false alarm," which is clearly undesirable. Furthermore, in the enclosed modules of spacecraft, the detection of some noncombustion conditions, such as overheating, smoldering, and catalytic decomposition is also essential.

Fire detection devices thus work on the general principles of temperature rise, radiation, chemical species, and particle detection. In the earliest U.S. manned spacecraft, fire sensors were unnecessary since the astronauts functioned as detectors. Beginning with the Skylab project, spacecraft modules became too large and complex for reliance on human observations. The Skylab fire detector was a radiometer, sensitive to ultraviolet radiation at less than 270 nm, which responded to OH radicals generated by a fire. The Shuttle uses nine ionization-type detectors (Fig. 5). These are analogous to commercial smoke detectors, operating on the principle that smoke particles impede the mobility of air ions in a chamber, changing the current level to trigger an alarm. For the Shuttle, forced-air fans at each detector provide a flow path to insure the transport of smoke particles to the detector (Ref. 2).

New designs for spacecraft fire sensors incorporate a variety of detection techniques. DeMeis mentions infrared detectors for flames and coaxial wire detectors for overheating (Ref. 4). In the future, fire detection in spacecraft must look for rapid response, localized identification of hazards, and light-weight sensors. Multiple-pattern recognition methods will sense incipient fires through a combination of independent signatures to minimize false alarms. Overheating problems with individual components may be identified by volatile chemical coatings to release indicators to provide recognizable signatures. An alternative means of fire detection, whose value in microgravity is being determined, involves a condensation nuclei detector, which counts smoke particles by condensed water droplets around each particle (Ref. 16). For the long-duration Space Station, a means of calibrating fire or smoke detectors in-situ will be necessary. Underlying all of these technology goals is the need for more basic research on the identification of fire signatures of spacecraft materials in microgravity.

FIRE EXTINGUISHMENT

Fires are extinguished through several physical and chemical means. The burning materials can be removed, the oxidant can be inerted, the reaction can be cooled, or the reaction can be chemically inhibited. The Mercury and Gemini spacecrafts had water available, but they had no systems dedicated solely for fire extinguishing. The Apollo spacecraft had a hand-held fire extinguisher, which contained water and a cellulose gel that formed a foam when sprayed. The 100-percent-oxygen atmosphere of the early spacecrafts aggravated the flammability of most materials, and tests showed that water was the only effective extinguishant. In the more conventional atmospheres of recent spacecraft, halogenated hydrocarbon fire extinguishers are supplied. For the Shuttle (Fig. 5), there are both fixed and portable fire extinguishers. Important features in the Shuttle cabin are designated ports in the instrument panels to insert a portable fire extinguisher nozzle if it is necessary to control a fire within the instrument rack.

The use of halogenated hydrocarbon (Halon) fire extinguishers in the Shuttle is based on the history of the use of these extinguishers in aircraft. A comprehensive review of this class of fire extinguishing agents was the subject of a 1973 symposium (Ref. 17). The most widely used halogenated compound is Halon 1301 (bromotrifluoromethane, CF_3Br), which acts as a combustion inhibitor by generating bromine atoms to react with the OH radicals to stop the combustion chain reaction. Halon 1301 is an effective extinguishant in volume concentrations up to 6 percent, but it is not as useful for deep-seated fires where cooling of the reacting gases is required. Another negative aspect of the use of Halon 1301 is the toxicity and corrosiveness of the halogen acids, HBr and HF, which are formed as decomposition products. In open spaces, these products are easily dispersed, but in a spacecraft, atmospheric contamination after even minor fires is a great concern. The agent itself, when leaked or discharged (it is a gas at normal conditions), can also be toxic.

Recent reviews on spacecraft operations (Ref. 4, for example) have recommended greater attention to fire extinguishants other than the Halon 1301. Some agents, such as deionized or sprayed water, nitrogen, and carbon dioxide are already proven in ground practices; yet their effectiveness in space is unknown. For an uncontrollable fire, space offers the option of venting. In the Space Station, the crew could abandon a module, vent it slowly to extinguish the fire, and ultimately return to the module after repressurization and cleanup. Again, underlying all of the technology goals is the need for further investigation of the peculiarities of flame propagation and extinction in microgravity.

MATERIALS ASSESSMENT

Materials for usage in inhabited spacecrafts have always been strictly controlled. The 100-percent oxygen atmosphere of the early spacecraft created a hazardous situation in which few materials, even metals, are truly nonflammable. The stringent materials requirements acted as a catalyst for the creative invention and development of "space age" materials. The 1971 Conference on Materials for Improved Fire Safety (Ref. 18) was a forum for the review of the progress in nonmetallic structural materials, foams, and insulations, as well as a review of the new flammability testing and acceptance procedures. Materials screening involves the verification of the acceptability of the bulk material followed by qualification testing in specific configurations. Flammability tests adapted for spacecraft included conventional flash point tests as well as unique upward propagation, downward propagation, drip ignition, short-circuit ignition, and auto-ignition tests.

Current spacecraft have less hazardous atmospheres than earlier spacecraft (sea-level air), but fire safety measures through materials control are still imperative. At present, NASA imposes the flammability and offgassing requirements of the NHB 8060.1B handbook (Ref. 3) in addition to other documented specifications on strength, corrosion resistance, and vacuum permeability. Material control procedures are through computerized tracking systems, with review of approvals and waivers.

The long-duration habitation and the wide range of living and working activities in the Space Station will expand the range of desired materials on board. Not only must inventoried materials be considered, but also extraneous items or contraband. Papers, books, films, recreational items, non-issue clothing items, and souvenirs will be brought on board. Secured, fire-resistant storage areas for personal items may be the only practical approach.

The aim of present day flammability testing is to provide useful measurements that can be interpreted on the basis of the underlying chemical and physical principles. Material tests, of necessity, are usually on small scale samples. The tests serve to predict full-scale behavior to guide the ultimate quality assurance using, as far as possible, standardized methods and procedures. Hilado has assessed various fire response test methods for suitability in screening aerospace materials (Ref. 19). Several recommended calorimetry methods, introduced by the National Bureau of Standards, Factory Mutual Research, Ohio State University, and Arapaho Chemicals, use standardized chambers to determine heat release rates, oxygen consumption, smoke release, and toxic vapor generation to characterize materials. The advantage of the use of standardized industry methods for fire safety is the opportunity to generalize techniques with precision limits determined from interlaboratory cooperative testing. For the Space Station, expansion of the NASA methods of NHB 8060.1B to include the generalized procedures will assist users by allowing more simplified and convenient screening of research and housekeeping materials.

The long-duration operation of the Space Station demands attention to time-related flammability testing, which would allow for deterioration and aging of materials. The unique low gravity environment makes specialized testing necessary, including methods appropriate to determine spontaneous ignition and low temperature combustion (smoldering). Since practical material testing in microgravity is very difficult, the goal of spacecraft materials assessment is to develop statistical or corrective techniques that can be used to interpret normal-gravity flammability test results in view of the more (or less, perhaps) stringent criteria for microgravity. Additional research projects in microgravity should address the concerns for spontaneous ignition, low temperature combustion (smoldering), and changes in material flammability with aging, all matters of particular importance for the Space Station.

SPACECRAFT ATMOSPHERES

The confidence of ground experience would seem to favor the retention of a sea-level oxygen-nitrogen atmosphere in spacecraft. Nevertheless, research has shown that alternative atmospheres can have advantages for fire safety. These are atmospheres that inhibit combustion and yet support human life. Table I shows standard atmospheric values at several altitudes. On the ground, humans can acclimate in permanent settlements at altitudes at least as high as 2800 m (9200 ft), the altitude of Quito, Ecuador. Thus, human activities are feasible over a range of atmospheric pressures from below 74 to 100 percent of sea level, corresponding to oxygen partial pressures of 16 to 21 kPa. The amount of nitrogen or, within limits, the total pressure of the atmosphere is immaterial for human sustenance. For combustion, on the other hand, an atmosphere is required with a minimum concentration, or mole percent, of oxygen. The presence of nitrogen affects combustion because combustion energy is used to heat the inert atmosphere, cooling and possibly quenching the flame.

As a consequence to these differences in atmospheric effects, it is evident that atmospheres with partial pressures acceptable for humans, but with reduced mole fractions of oxygen, could reduce fire hazards in spacecraft. This use of a modified spacecraft atmosphere had been proposed about 20 yr ago based on simple flame-spread tests (Ref. 20). A further application of this principle is the proposal of nitrogen flooding to combat fire emergencies in submarines, where total pressure is increased to suppress fires by lowering the oxygen concentration while retaining the life-supporting oxygen partial pressure (Ref. 21).

Alternatives to reduced-oxygen atmospheres are those with gases other than nitrogen as the inert constituent. Helium, long used as the diluent in diving atmospheres, appears to inhibit ignition, but it promotes the spread of established fires. Desirable fire suppression requires a high specific heat per mole. Studies by researchers such as Huggett (Ref. 22) have proposed the substitution of fluorinated hydrocarbons, such as carbon tetrafluoride, CF_4, for at least part of the nitrogen in a fire-safe atmosphere. The fluorinated hydrocarbons not only suppress flame spread by their high specific heat, but can produce reaction-inhibiting species analogous to the action of Halon 1301 extinguishant. These halogenated gases appear to be physiologically inert, but confidence in their usage must be demonstrated by long-term testing.

A very interesting set of suggestions has come from the 1986 NASA Lewis Workshop on Spacecraft Fire Safety. A group of participants proposed three alternative spacecraft atmospheres, judged to provide a more fire safe environment, for scientific investigation and technology development. These atmospheres, in the priority given, are:

(1) 150 kPa total pressure (1.5 atm); 12 mol oxygen; nitrogen diluent;
(2) 100 kPa total pressure (1.0 atm); and minimum oxygen concentration; nitrogen diluent;
(3) atmospheres with diluents other than nitrogen.

The first recommendation is an atmosphere that retains the sea level partial pressure of oxygen. The mole percent of oxygen, however, is low enough that fire hazards should be greatly reduced. Unfortunately, the higher total pressure may call for more complex and heavier spacecraft structures. The second recommendation avoids this total-pressure difficulty. A minimum oxygen mole fraction of 16 percent would correspond both to standard earth conditions at 2200 m (7200 ft) altitude (Table I) and the usual cabin atmosphere in long-range commercial aircraft. The third recommendation is based on the innovative substitute diluent proposals just discussed, but this alternative is the least likely for consideration because of unknown cost, complexity, and human response factors.

AIRCRAFT AND UNDERWATER ANALOGIES

It is obvious that spacecraft fire safety technology must recognize the research and methods established for building codes and, more particularly, for aircraft and underwater safety. Certainly, there is need for continued and expanded use of the analogies from these neighboring spheres of technology.

The airplane operating environment has obvious differences from that of spacecraft. These are normal gravity, some access to the external atmosphere, and short-term possibilities for escape and rescue. Nevertheless, many of the spacecraft fire techniques in risk management, fire detection, extinguishment, and materials assessment can be traced to aircraft fire controls. For example, the review by Botteri on aircraft fire safety (Ref. 23) discusses aircraft techniques on failure criteria, fire detection, Halon extinguishers, and inert gas generation. Some of these have been adapted or are under consideration for spacecraft. Fire detection and extinguishment in aircraft has been discussed in more detail by Waldman (Ref. 24). The Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee Report includes a number of recommendations that certainly apply to spacecraft as well as to aircraft (Ref. 25). In brief, pertinent sections of the report refer to toxic and smoke hazards, chemical product detection, animal testing, toxicity standards, and material ratings.

Underwater technology would appear to provide further opportunities for spacecraft fire safety analogies since submarines operate in a hostile external environment with self-contained environmental controls. Of course, the submarine contents are under normal gravity, and the internal pressure is less than the external atmosphere. This makes leakage rather than venting a hazard. A review published over 20 yr ago discusses atmospheric contaminant control in spacecraft by analogy to submarine procedures (Ref. 26). Atmospheric control has direct application to fire safety because of the question of contamination and toxicity following a fire or pyrolysis. This subject of human effects was covered in the 1986 NASA Lewis Spacecraft Fire Safety Workshop, but it lies outside the scope of this paper.

Fire suppression techniques discussed by Carhart and Fielding for submarines (Ref. 27) also include methods under consideration for spacecraft, namely Halon systems, water foams, carbon dioxide, and nitrogen. The nitrogen flooding technique for large fires, already noted, was proposed for submarines designed for high-pressure containment. The method, however, cannot be dismissed as completely unsuitable for spacecraft. A pressure increase of no more than 60 kPa may be sufficient, according to Ref. 21.

CONCLUDING REMARKS

This paper has presented the progress and needs of fire safety applicable to human crew spacecraft, with some emphasis on the requirements for the Space Station. Future spacecraft fire safety studies seek solutions to two apparently contradictory problems: the need for more stringent measures because of the long duration and complexity of the Space Station missions, and the need for less stringent measures to encourage scientific and commercial usage in the same missions. This paper has presented the state-of-the-art in the underlying microgravity combustion field and in technology developments in fire detection, extinguishment, material assessment, and spacecraft atmospheres. For future work, it appears that the emphasis will continue on combustion fundamentals to establish relationships for fire propagation and extinction in the spacecraft environment.

A further result of the review of spacecraft fire safety is the recognition of the need for more generalized and flexible standards and methods. The attainment of this goal is greatly assisted by cooperative sharing of aircraft and underwater information and adaptation of existing knowledge. There is a strong promise of greater involvement of propulsion safety expertise, as exemplified by the participation of the JANNAF members.

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TABLE I. - OXYGEN CONTENT AT STANDARD ALTITUDES

Altitude		Total pressure		Oxygen partial pressure		Comments
m	ft	kPa	psia	kPa	Percent of sea level	
0	0	101.3	14.7	21.23	100	a
1000	3280	89.0	13.04	18.83	89	
2000	6560	79.5	11.53	16.65	78	
2213	7260	77.4	11.23	16.21	76	b
3000	9840	70.1	10.17	14.69	69	
4000	13120	61.7	8.94	12.92	61	
4843	15890	55.2	8.00	11.57	54	d
5000	16400	54.0	7.84	11.32	53	
6000	19700	47.2	6.85	9.89	47	
7000	23000	41.1	5.96	8.61	41	
8000	26000	35.7	5.17	7.47	35	
8222	26980	34.5	5.00	7.23	34	c
9000	29000	30.8	4.47	6.45	30	

Notes: a. Oxygen partial pressure calculated at geopotential altitudes shown based on invariant composition of 20.94 mol (vol) % of oxygen.

b. Practical minimum oxygen partial pressure corresponding to earth altitude and commercial flight acclimatization.

c. Present space suit pressure, supplied with 100 percent oxygen.

d. Proposed future space suit pressure. Oxygen content could range from 29 mol % (b limit) to 38 mol % (sea level partial pressure.

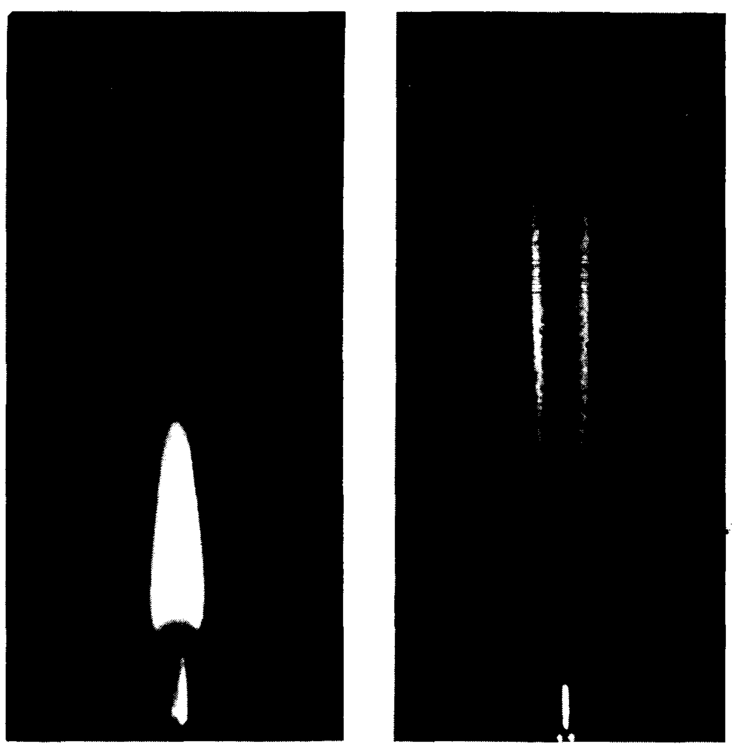

FIGURE 1. - EXAMPLES OF GAS JET DIFFUSION FLAMES IN NORMAL (EARTH) GRAVITY AND IN MICROGRAVITY.

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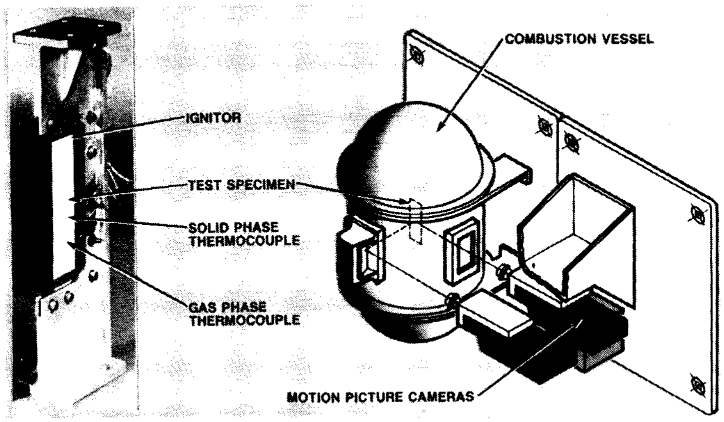

FIGURE 2. - SOLID SURFACE COMBUSTION EXPERIMENT APPARATUS, TO STUDY FLAME SPREAD OVER SOLID SPECIMENS IN SHUTTLE FLIGHTS.

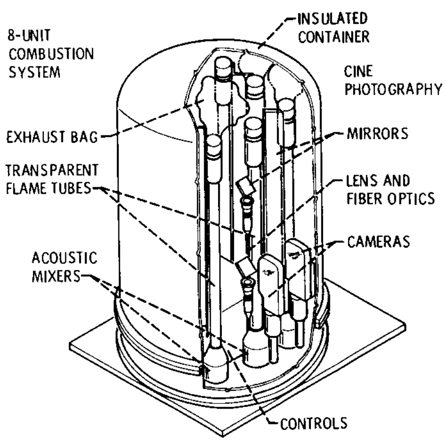

FIGURE 3. - PARTICLE CLOUD COMBUSTION EXPERIMENT APPARATUS, TO STUDY FLAME PROPAGATION AND EXTINCTION IN PARTICULATE-AIR MIXTURES IN SPACECRAFT FLIGHTS.

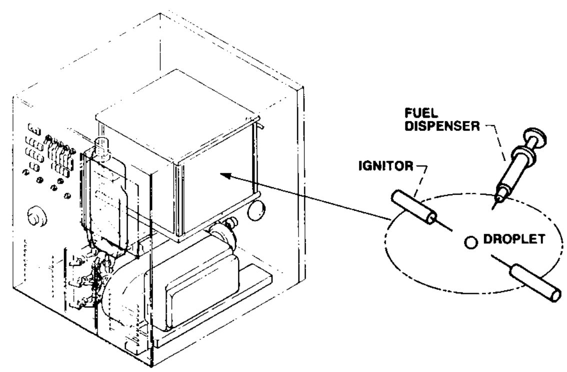

FIGURE 4. - DROPLET COMBUSTION EXPERIMENT APPARATUS, TO STUDY BURNING OF SPHERICAL LIQUID DROPLETS IN SPACECRAFT FLIGHTS.

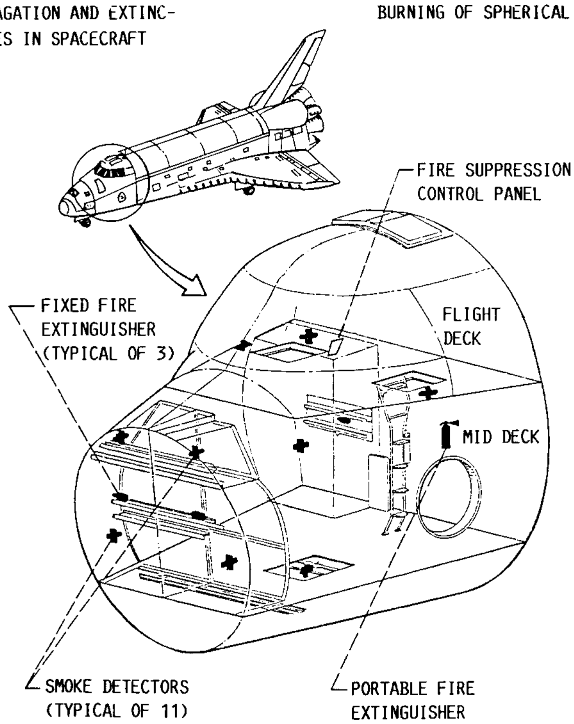

FIGURE 5. - FIRE PROTECTION IN THE SHUTTLE CABIN.

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15. Supplementary Notes

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16. Abstract

This paper reviews the state-of-the-art in fire control techniques and identifies important issues for continuing research, technology, and standards. For the future permanent orbiting facility, the Space Station, fire prevention and control calls for not only more stringent fire safety due to the long-term and complex missions, but also for simplified and flexible safety rules to accommodate the variety of users. Future research must address a better understanding of the microgravity space environment as it influences fire propagation and extinction and the application of the technology of fire detection, extinguishment, and material assessment. Spacecraft fire safety should also consider the adaptation of methods and concepts derived from aircraft and undersea experience.

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