FIRE EXTINGUISHMENT AND INHIBITION IN SPACECRAFT ENVIRONMENTS

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BACKGROUND

The confinement of personnel for long periods of time in the relatively small volumes of spacecraft introduces several unique hazards, in particular: (1) the continuous accumulation of trash, which might support combustion; (2) the extensive use of fire-retarded materials, which once ignited tend to produce very toxic products of combustion; and (3) the need to rapidly detoxify the cabin atmosphere immediately following a fire since (a) personnel escape is impractical, (b) venting to space with provision for replacement of the cabin atmospheres incurs a severe design weight penalty, (c) toxic products of combustion tend to be highly corrosive, and (d) the assigned spacecraft mission must presumably be continued.

In addition, the use of an artificial atmosphere inevitably introduces uncertainty as to the ambient oxygen concentration, which strongly influences the potential fire hazards. Materials and extinguishment methods must be tested under worst-case conditions corresponding to the maximum oxygen concentration. Figure 1 (from ref. 67) shows the strong influence of ambient oxygen concentration. Flame temperatures, material ignitibility, and burning rates depend primarily on the ambient oxygen concentration; hence combustion data are correlated by the horizontal zones in the figure, defined by limits of mole percent oxygen. Human breathing effectiveness, however, depends primarily on the partial pressure of oxygen, represented by the broken lines in figure 1 (a normal atmosphere has 21-kPa oxygen partial pressure). As a result one could noticeably decrease fire hazards by maintaining the partial pressure of oxygen corresponding to terrestrial conditions, while increasing the partial pressure of nitrogen to some higher value, perhaps to 200 to 300 kPa (2 or 3 atm). The dependence on total pressure (at low total pressures) indicated in figure 1 is primarily due to changes in buoyancy forces per unit volume. Fortunately, the reduction of buoyancy forces tends to reduce fire hazards, because less ambient oxidant is drawn into the flame zone for support of combustion.

The virtual elimination of buoyancy forces in a microgravity environment introduces important fundamental changes in combustion mechanism - even though a gentle breeze is usually present for ventilation purposes. It is clearly impractical to perform material acceptance tests (and perform realistic fire suppression tests) in a microgravity environment. As a result we must rely on a thorough theoretical and conceptual understanding of fire behavior mechanisms when extrapolating our terrestrial experience to spacecraft conditions. This demands a continuing basic research effort to provide a firm scientific foundation for any proposed extrapolations. For example, the reduced fluid flow rates under microgravity conditions result in longer flow residence times, probably reducing the effectiveness of extinguishing agents such as Halon 1301 that act by slowing gas-phase kinetic reaction rates. These longer flow residence times may also allow for more soot formation and greater fractional radiant heat transfer under microgravity conditions. Halon 1301, when introduced into gaseous hydrocarbon fuels, is known to strongly encourage soot formation

and probably increase the radiant heat transfer from the flames. While this augmented radiant heat transfer may tend to quench the flames, it is also likely to increase the soot and carbon monoxide output; and it may induce higher overall burning rates if the fire is large enough to be controlled by radiant heat transfer to the pyrolyzing solid fuel. These issues clearly demand further fundamental research.

As we approach the 21st century, activities in space will become increasingly routine. People will demand higher level of safety from unwanted fires. Even today astronauts receive very little fire safety training. Future manned spacecraft missions will be of longer duration, be likely to have more objectives, and be expected to survive accidental fires. Terrestrial fire-safety experience dictates that unwanted ignitions will occur and that the most difficult situations will be associated with unexpected fire scenarios. Presumably, all anticipated hazards can be controlled by careful design. Thus our major challenge at this time is to choose and develop a suitable general purpose fire-fighting technology that can be used to handle unexpected hazards with relatively little personnel training. Meanwhile, we should actively pursue the relatively easier challenges of designing specific fire protection measures for clearly identified hazards.

ELECTRONIC EQUIPMENT

Spacecraft generally have a lot of electronic equipment, which presents a likely source of fire ignition due to overheated components. Such equipment is generally in modularized compartments to insure its reliability and protect it from outside electrical, mechanical, and thermal disturbances. In general, one needs to gain access to the compartment interior only when there is a clearly identified faulty component that must be replaced or repaired. All other access generally occurs through panel controls, gauges, and connectors. Nowadays, terrestrial computers are sometimes fire-protected by installing self-contained automatic Halon 1301 canister extinguishers within the computer cabinet. Halon 1301, however, introduces severe toxicity and corrosion problems. Instead, it might be much more desirable to inert the atmosphere within the compartments through use of an onboard nitrogen inert gas generation system (OBIGGS), using molecular sieve or permeable membrane techniques to provide continuous purging. The compartments would have to be sealed and possibly provided with suitable heat exchangers. This approach would prevent ignition and reduce its concomitant damage, cleanup, and potential corrosion hazards. It would also minimize any fire-induced outgasing of halogens from circuit boards and cable insulation. The sealing of electronic compartments would be quite advantageous in terms of reducing corrosion problems within the compartment due to attack by extinguishing agents or products of combustion from fires taking place outside the compartment.

GENERAL-PURPOSE FIRE EXTINGUISHMENT

It is essential for spacecraft to be provided with a general-purpose fire extinguishing system that is capable of handling a very broad range of fire threats both in terms of origin and magnitude. The choice of extinguishing system needs to be made as soon as possible to allow time for technology development tailored to spacecraft environments. Present day general-purpose systems include water sprays, dry powder, foam, CO_2 or N_2 inerting, and Halon 1301.

Dry powder and water-based foam present definite cleanup problems in a spacecraft and will not be discussed further here.

Gaseous Inerting

Nitrogen inerting has the advantage over carbon dioxide inerting of not requiring onboard storage of an additional gas. Nitrogen also introduces fewer physiological effects. It, therefore, has definite potential. Recently, the U.S. Navy has tested N_2-pressurization as a method for combating submarine fire hazards and has found it to be quite effective. Figure 1 suggests that for deep-seated fires involving glowing combustion (incomplete combustion), oxygen concentration must be greatly reduced through extensive inerting. Currently, the U.S. Navy is not actively pursuing this approach because the onboard storage of extra nitrogen incurs a considerable weight penalty. Carbon dioxide would have an even greater weight penalty, and we shall not consider it further here. This leaves only Halon 1301 and water-sprays as candidate fire fighting agents, which we shall now consider in more detail.

Halon 1301 (Bromotrifluoromethane, CF_3Br)

Halon 1301 is a nonflammable gas that chemically inhibits gas-phase combustion by releasing bromine atoms, which can repeatedly scavenge OH radicals necessary for combustion. On a pound-for-pound basis, it is typically two-and-a-half times more effective than carbon dioxide as a fire-extinguishing agent. It is effective at a volumetric concentration of 6 percent against liquid-fuel (Class B) and electrical (Class C) fires as well as most surface fires involving ordinary combustibles (Class A). It is ineffective against deep-seated (Class A) fires because it does not directly cool the solid fuel and does not chemically impede glowing combustion reactions. Such glowing reactions are less important because they do not spread rapidly and can be extinguished with small amounts of water once a fire is otherwise under control.

Halon 1301 itself is noncorrosive. It is also the least toxic of the various types of Halons at their equivalent fire fighting concentrations. However, the products of combustion from fires being suppressed by Halons are highly toxic and corrosive. This means that one must achieve rapid fire suppression and make provision for immediately cleaning up the atmosphere after a fire. This is a very difficult technological task in a spacecraft environment, where one does not have ready access to a supply of fresh air for several volume changes while flushing the products out of an occupied cabin. If the personnel could retreat to a secure area of the spacecraft, the task would be made easier by venting all the contaminated atmosphere to outer space; however, all components of the spacecraft would have to be designed to withstand a full vacuum.

The most formidable obstacle to the use of Halon 1301 is the toxicity of the agent in its original "neat" state. Numerous studies (refs. 68 to 71) have been made on its toxicity, leading to the recommendations summarized in table I (refs. 68 and 71 to 73). Reference 69 states: "Three healthy male volunteers were exposed to Halon 1301 in a controlled-environment chamber for the purpose of monitoring their physiological and subjective responses to a series of Halon 1301 gas concentrations ranging from 1000 parts per million to 7.1 percent for periods of 30 minutes. The first untoward responses were observed to occur

during exposure to 4.3 percent and 4.5 percent. These consisted of a sensation of light-headedness and dizziness accompanied by a feeling of euphoria occurring within 2 minutes of exposure. Exposure to 4.5 percent for 10 minutes resulted in an impairment in tests of balance in one of the three subjects. A second subject evidenced mild impairment when exposed for an additional 20 minutes. Exposure to 7.1 percent produced mild changes in tests of balance in one individual and severe impairment in a second subject who concomitantly experienced a decrement in eye-hand coordination. In the well-lighted environmental chamber all subjects demonstrated their ability to safely exit over a 1-minute period from the contaminated zone. No untoward cardiovascular responses were observed. The untoward physiological and subjective responses observed were short-lived following cessation of exposure."

It is clear from these studies that a spacecraft would have to be provided with some means for chemically cleaning Halon 1301 from the atmosphere following the extinguishment of a small fire. The author is unaware of any such available technology for this purpose. It is for this reason that the U.S. Navy has not seriously considered using Halon 1301 for suppressing submarine fires.

Water Sprays

Water sprays are effective against fires involving ordinary solid combustibles (Class A), liquid fuels (Class B), and electrical fires (Class C). On a pound-for-pound basis, water hand-held extinguishers are about as effective as Halon 1301 extinguishers for surface fires and much more effective for deep-seated fires. Liquid water extinguishes fires primarily by cooling the vaporizing fuel. Water also cools the fire zone and surroundings as well as providing some smothering of the fire.

Portable hand-held extinguishers producing solid streams are not recommended for Class B and Class C fires. A short solid stream of water can splatter a pool of liquid fuel and might conduct electricity when in contact with a high voltage. However, solid streams are very useful when one wishes to project the water over long distances. Solid streams of city-water (containing electrically conducting ions) present a definite shock hazard when used within four feet of high voltage (600 V) equipment. Sprays are not hazardous. Shock hazards of accumulated water could presumably be significantly reduced by use of a deionizing water filter.

Fine sprays of water can be remarkably effective against vigorous fires in compartments. The U.S. Navy (ref. 74) has extinguished fully developed liquid hexane and heptane fires in 0.8-m^2 (9-ft^2) and 2.2-m^2 (24-ft^2) pans within 6- by 6- by 3-m (20- by 20- by 10-ft) enclosures within 9 sec at a water application rate of 1.3 l/sec (20 gal/min). Factory Mutual Research has demonstrated similar rapid extinguishment in its bedroom-fire test series. Apparently, the vigorous spray injection causes the fine drops to be deposited on all exposed surfaces preventing further fuel pyrolysis. Extinguishment occurs before enough water mist could accumulate in the gas volume to render it noncombustible. One would need to have one mass unit of liquid water mist for each three mass units of air to reduce the resultant equilibrium flame temperature to below 1500 K, which is around the temperature necessary to prevent gaseous combustion. Test observations indicate extinction occurs with far less water. Generally, one needs an order of magnitude less water if the water is

used for direct cooling of the pyrolyzing or vaporizing surface. Fine sprays are less effective for shielded fires, although they do cool the surroundings and allow access for manual extinguishment.

The most significant advantages of water sprays for spacecraft fire extinguishment are the absence of adverse toxicological effects, the natural scrubbing action of water drops in cleaning the atmosphere, the ease of agent cleanup using the spacecraft ventilation system dehumidifier, the small mass of agent needed, and the fact that ample liquid water is already available on the spacecraft for other purposes so that little weight penalty is involved for fire protection. Electronic equipment subjected to water sprays generally recovers full functionality after the liquid water dries out. As discussed earlier, it might be desirable to keep spacecraft electronic equipment in sealed inert gas containers to avoid taking the equipment even temporarily out of service.

The use of water sprays in microgravity environments introduces a variety of scientific issues. There is a vast literature on the behavior of liquid sprays. Computer models are available (refs. 75 and 76) for calculating spray dynamics with and without gravity. These models follow individual typical drop trajectories and include effects of turbulence on the gas-flow dynamics. A suitable water pressure, spray angle, and orifice diameter need to be chosen to provide the desired nozzle water-flow rate and drop diameter leading to rapid deposition of water on exposed fuel surfaces. It might be desirable to employ a hose line with an adjustable nozzle similar to that of a garden hose to control the water flow rate and throw distance of the spray.

It would be useful to employ these computer models to study the effects of water-flow rate, drop size, and spray momentum on the speed and uniformity of water deposition on shielded and unshielded surfaces with and without the presence of forced ventilation. Very fine drops can be carried by the general gas motion behind shielded surfaces, but they will settle out (or be flung out) more slowly. Large drops tend to travel in more straight lines, directly impacting unshielded surfaces with little, if any, water reaching shielded surfaces. The spray itself can generate considerable gas motion. It would be interesting to know whether there is an optimum drop-size range leading to relatively fast and uniform surface deposition. In particular, one would like to know how this optimum drop size depends on the presence or absence of gravity. Conclusions drawn from such a mathematical study could certainly provide insight useful in selecting a practical spacecraft water spray fire protection system.

The U.S. Navy favors the use of fine-drop water sprays for submarine fire protection and is currently developing a fixed-nozzle high-pressure system (ref. 74). The needs and constraints of NASA are quite similar to those of the U.S. Navy. It is recommended that NASA seriously consider the adoption to a hose line and water spray for its general-purpose fire protection needs.

CONCLUSIONS

It is essential that NASA develop a comprehensive approach to fire extinguishment and inerting in spacecraft environments. Electronic equipment might readily be protected through use of an onboard inert gas generating system (OBIGGS). The use of Halon 1301 presents serious technological challenges for

agent cleanup and removal of the toxic and corrosive products of combustion. Nitrogen pressurization, while effective, probably presents a serious weight penalty. The use of liquid water sprays appears to be the most effective approach to general-purpose spacecraft fire protection.

TABLE I. - ALLOWABLE HALON 1301 EXPOSURES

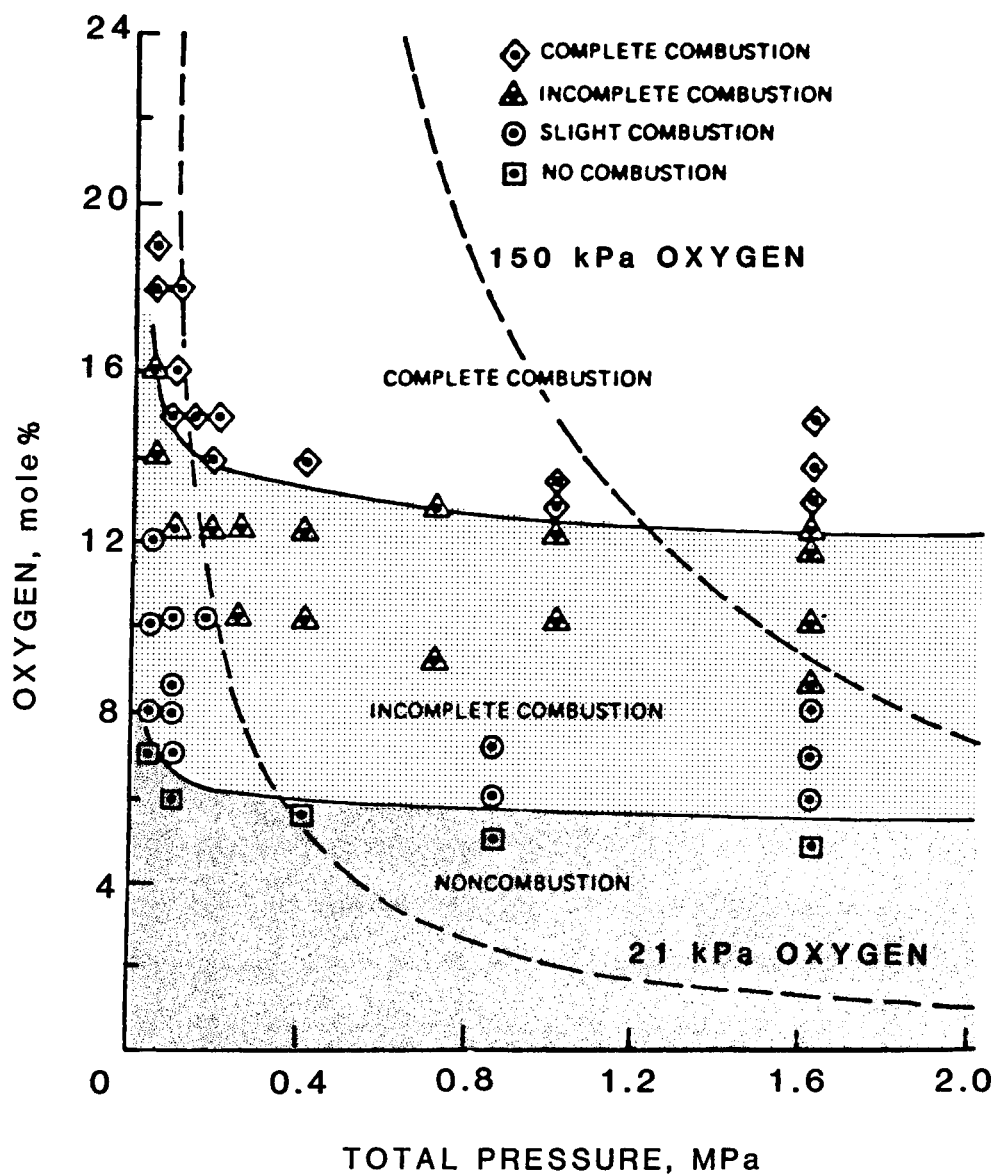| Organization	Concentration, vol %	Time	Reference
OSHA	0.1	8 hr/day, 40 hr/wk	72
NFPA(12A)	Up to 7 7 to 10 10 to 15 >15	15 min 1 min 30 sec 0	73
FAA	Product of percent and minutes	≤ 10	71
U.S. Air Force	6	5 min	68

Figure 1. - Varying degrees of combustion in an oxygen-nitrogen atmosphere (ref. 67).