FIRE SAFETY PRACTICES IN THE SHUTTLE AND THE SPACE STATION FREEDOM

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ABSTRACT

The Shuttle reinforces its policy of fire-preventive measures with onboard smoke detectors and Halon 1301 fire extinguishers. The forthcoming Space Station *Freedom* will have expanded fire protection with photoelectric smoke detectors, radiation flame detectors, and both fixed and portable carbon dioxide fire extinguishers. Many design and operational issues remain to be resolved for *Freedom*. In particular, the fire-suppression designs must consider the problems of gas leakage in toxic concentrations, alternative systems for single-failure redundancy, and commonality with the corresponding systems of the *Freedom* international partners. While physical and engineering requirements remain the primary driving forces for spacecraft fire-safety technology, there are, nevertheless, needs and opportunities for the application of microgravity combustion knowledge to improve and optimize the fire-protective systems.

INTRODUCTION

Fire safety in spacecraft has been cited as one practical motivation for advancing microgravity combustion research (ref. 1). Current spacecraft fire protection, however, is based largely on established fire-safety practices used in enclosed compartments, such as aircraft (ref. 2). The application of fundamental, quantitative information from microgravity combustion research could promote greater efficiency in the design and operation of protective systems, lessen restrictions on the use of materials and operations in space-based hardware, and reduce excessive safety factors and false alarms. Certainly, the advent of the complex, permanently orbiting Space Station *Freedom* offers an opportunity for novel and improved spacecraft fire-safety techniques derived from a thorough understanding of fire behavior in low gravity (ref. 3).

This paper is thus a review to acquaint the microgravity combustion research community with current and proposed fire-safety practices and critical issues for U.S. human-crew spacecraft and to suggest relevant fields where microgravity combustion research may promote spacecraft fire safety.

HAZARD ANALYSES FOR SPACECRAFT

General Strategies

The major emphasis in spacecraft fire safety is on fire prevention through control, if not elimination, of one of the three elements necessary for fire, *i. e.*, fuel, ignition, and oxygen (ref. 4). For the first element, the control is based on a policy of qualifying acceptable materials for spacecraft use through tests of the resistance to upward (in normal-gravity) flame spread following exposure to promoted ignition. Of course, many necessary spacecraft items fail this test (including articles made from paper and fabrics). Usage of these materials is permitted in limited quantities under prescribed conditions of fire-safe storage. For the second element, control of ignition is through standard practices of electrical grounding, circuit breakers, pressure containment, and the like. There is no control of the third element, oxygen. The Shuttle atmosphere is sea-level air, which is enriched to 30% oxygen at a reduced total pressure of 72 kPa for prebreathing prior to an extravehicular activity. The use of fire-resistant, reduced-oxygen atmospheres for human support in submarines and other enclosed habitats has been investigated (ref. 5). For the Shuttle and the initial phases of the Space Station *Freedom*, however, design and operational considerations eliminate the consideration of other than conventional atmospheres (ref. 4).

Fire Scenarios

Absolute fire prevention is impossible and perhaps not even desirable if possible. Spacecraft fire safety must address the tradeoff of minimum risk against operational practicality, where a minimum, residual risk level can be defined as the consequences of a worst-case fire that causing possible component damage that can suspend some operations temporarily but no human injuries (ref. 6). For the Shuttle, plausible fire-initiating scenarios are electrical breakdowns (shorts, overloads, and arc tracking) or electromechanical overheating (motors, rotating equipment, heaters). For *Freedom*, potential fire-causing scenarios are more numerous. W. Fuller and M. Halverson (cited in ref. 7) conducted a qualitative risk assessment for the station with initiating fire scenarios covering electrical shorts, faults in electrolysis units, oxygen leaks, chemical reactions, faulty experiments, or improper crew or ground actions.

A complete strategy of fire protection in spacecraft thus proceeds from the assumption that fires or their precursors will have a finite probability of occurrence. Onboard fire safety in current and proposed spacecraft must then concentrate on fire detection, suppression, and post-fire restoration. The description and evaluation of these fire-responsive techniques are the primary scope of this review.

BRIEF HISTORY OF U.S. SPACECRAFT FIRE SAFETY

The atmosphere in the early spacecraft, Mercury, Gemini, and Apollo, was 100% oxygen, an atmosphere in which no common organic material can truly resist fire spread. This failing was emphasized by the disastrous Apollo 204 fire in 1967, occurring during ground testing at sea-level total pressure. The investigation of the Apollo fire led to the development of new plastic materials, the adaptation of the present flammability-assessment methods, and the use of a diluted oxygen atmosphere for ground operations.

The development of fire-responsive techniques in spacecraft has been slower than that of fire-prevention measures (ref. 2). In the simple configurations of Mercury, Gemini, and Apollo, the crew members could observe the complete interior of the pressurized modules. Hence, the senses of the human crew were adequate to detect the initiation of a fire. The water gun for food reconstitution was designated for use as an emergency fire extinguisher. The Apollo spacecraft system added dedicated foam-agent fire extinguishers. It was not until the introduction of the first U.S. space station, Skylab in 1973 to 1974, however, that instrumented fire detection was incorporated in a spacecraft. The Skylab system used 30 line-of-sight ultraviolet flame detectors, placed throughout the station.

The Skylab space station also provided the environment for a pioneering test of low-gravity flammability, until recently the only quantitative study of fire behavior under low gravity. The Skylab study was an observation of the time-dependent flame front in the combustion of practical materials, including aluminized Mylar, Nylon, neoprene-coated Nylon, polyurethane foam, and paper. The materials were ignited in the Skylab atmosphere of 65% oxygen in nitrogen at 36 kPa total pressure. The flame-spread rate was calculated from comparisons of the flame-front position on successive motion-picture frames. Kimzey (ref. 9 and Appendix C of ref. 10) discussed the Skylab low-gravity and corresponding normal-gravity results and made the following key observations:

- Flame-spread rates are always lower in microgravity, with comparative rates ranging from .15 to .60 those in normal gravity.
- The visibility of a flame is significantly reduced in microgravity.

- Extinguishment by vacuum is effective, and the flame is extinguished when the available oxygen decreases sufficiently. A significant side effect is the flame intensification that develops during the initial phase of venting.
- Extinguishment by water is possible provided the application is controlled and adequate. If insufficient water strikes a burning material, it always causes a flareup that can scatter burning material.

The Skylab conclusions established the safety factor underlying the use of NASA normal-gravity flammability test assessments. That is, the material-acceptance criterion assumes that any item passing an upward-spreading normal-gravity test would be no more "flammable" in low gravity.

Recently, Pogue, one of the Skylab crew members, summarized his conclusions based on first-hand observations of the flammability study (ref. 11). Pogue also noted that flame-spread rates always are lower in low gravity than under corresponding normal gravity. However, he warned of some qualifications to be considered in interpreting the low-gravity flame-spread data for fire-prevention, detection, and extinguishment applications:

- Porous materials may capture oxygen within items to enhance microgravity flammability.
- Local agitation or displacement of air may occur from the thermomechanical response of burning materials.
- Local air flow may be induced by the usual cabin ventilation and air circulation systems.
- Local air flow may be induced by fire extinguishing.

FIRE PROTECTION FOR THE SHUTTLE

The early U.S. human-crew spacecraft were designed to meet specific mission objectives. The Shuttle, on the other hand, is a component of a complete Space Transportation System (STS). As originally conceived, the STS was to become the sole system for launching, maintaining, and retrieving orbiting satellites and space probes. For practical and economic reasons, the inclusion of all space activities into the human-crew STS has not occurred. Currently, world-wide launch operations use non-crewed expendable launch vehicles (ELV), and the U.S. retains a mix of the STS and ELV space transportation.

Fire Detection and Suppression Subsystem

The Shuttle normally has a pressurized atmosphere only in the front cabin, and the fuselage payload bay is exposed to the vacuum of space. For the increasing number of Shuttle missions dedicated to microgravity research, such as USML-1, the "payload" is the laboratory connected to the cabin by an air lock and tunnel. The pressurized laboratory shares its life-support system with the Shuttle cabin.

Fire protection for the Shuttle cabin and any pressurized laboratory is provided through a Fire Detection and Suppression Subsystem, which is a component of the Shuttle Environmental Control and Life Support System (ECLSS). The Shuttle cabin and its pressurized laboratories use ionization-type smoke detectors. Two units are located in each of three electronics bays for redundancy (a single-fault tolerant system). The smoke detectors are identical in principle to ionization detectors in common use in buildings and aircraft, although they have particular adaptations for spacecraft use (ref. 12). An integral fan creates a flow across entrance port to the ionization chamber to bypass larger, high-momentum particles, assumed to be dust, not smoke. The fan flow also insures adequate sampling in the absence of natural convection. Unfortunately, the bypass system may reject larger smoke agglomerates, possibly characteristic of a microgravity fire, reducing the detector sensitivity. The set points, determined by normal-gravity smoke-chamber calibrations, are established at very sensitive levels, however, well below those associated with visible smoke.

Fig. 1 shows the flight deck fire-protection panel, which has indicators for smoke-detector alarm status and actuators for the fixed fire extinguishers installed in the Shuttle cabin and in its payload-bay laboratory. These extinguishers, as well as additional portable extinguishers, are charged with Halon 1301 (bromotrifluoromethane). The manufacture and commercial use of Halon 1301, which is recognized as having a potential to deplete ozone in the stratosphere, is to be eliminated by international protocol in the next decade. There are no immediate plans for replacement of the Halon 1301 agent on the Shuttle. While Halon 1301 is a very effective agent for many fires, it can generate halogen acid gases, which are toxic and corrosive. Shuttle mission rules call for an immediate termination of the mission and return to Earth following discharge of a fire extinguisher.

Shuttle Mission Experience

Several minor incidents with fire-causing potential have occurred on Shuttle missions (ref. 13). On two reported occasions, the crew detected a smoke odor, and subsequent examination showed overheated components. In the first incident, on STS-6, April 1983, an odor was caused by the fusing of overheated wires near a space-processing unit. No degradation products were found in an atmospheric sampling; presumably, the carbon filter in the Shuttle ECLSS was effective in removing the trace compounds contributing to the odor. In the second incident, on STS-35, December 1990, the crew reported a smoke odor and a one-ampere current surge, before the failure of an overheated resistor in an elapsed-time circuit of a digital display unit shut off power to the unit. No atmospheric changes were otherwise noted. Recently, the STS-50 crew (July 1992) reported an odor and the failure of a medical apparatus, which was later traced to a blown electrical capacitor.

An incident of potentially greater consequence occurred on STS-28, August 1989, when a cable strain and insulation failure caused an electrical short circuit at a teleprinter unit. The crew observed sparks and 4 or 5 glowing embers during a period of about one to two seconds at the vicinity of the cable. One of the smoke detectors showed an increased particle-concentration level of 158 $\mu g/m^3$ for about 60 sec, with a momentary peak at 180 $\mu g/m^3$, levels well below the alarm set point of 2000 $\mu g/m^3$. Based on the observed mass of pyrolyzed material released from the burned wire insulation, calculations showed that the air-borne particle concentration could have exceeded the set-point concentration (C. Asuncion and B. Harkness, Rockwell International, internal letter, October 1990). Several reasons for the low observed smoke-concentration level reading were suggested:

- Some pyrolyzed mass was in particles larger than 50 µm (as observed by the crew) that bypassed the detector chamber.
- Some mass was in particles adsorbed on surfaces.
- Some mass was produced as gases rather than as aerosols.

The Shuttle mission experience confirms that breakdowns threatening incipient fires have finite probabilities. At the same time, the fire-protective systems and the alertness of the crew have been shown to be effective in recognizing and responding to these minor incidents.

FIRE PROTECTION FOR THE SPACE STATION *FREEDOM*

The proposed Space Station *Freedom* will not be the first permanently inhabited satellite system of this kind. *Freedom*, however, represents the first completely original approach to this space community, rather than a derivative assemblage with adapted components from earlier missions. *Freedom* will provide greatly expanded accommodations for life science studies, microgravity science and technology, earth observations, space probe launching, and satellite servicing. Obviously, potential hazard situations and consequent fire-protection demands will increase considerably over the proposed 30 years of continuous operations, compared to those for the short-duration missions of the Shuttle.

Preliminary Assembly and Atmospheres

Eventually, the Space Station *Freedom* assembly will evolve into a complex truss, module, and attachment assembly, the configuration usually publicized. The immediate concern of fire safety, however, is in the protection of the Man-Tended Configuration (MTC). The MTC is the minimum assembly of components necessary to sustain human activities within the station, a state anticipated to be completed in about six Shuttle-tended assembly operations, perhaps a year or so after the date of the first element launch (fig. 2). The working volume of the MTC consists of three pressurized modules: a laboratory, resource node, and docking adapter (ref. 14). The module atmosphere will have a composition of 30% oxygen in nitrogen at a total pressure of 72 kPa to permit ready egress for space-suited extravehicular activities, without the need for prebreathing to avoid decompression sickness (ref. 15). Clearly, this enriched-oxygen atmosphere increases the potential fire hazard over that of standard air. *Freedom* will be occupied by the crew only during the Shuttle-tended periods from the MTC until the final configuration of the Permanently Manned Capability. The pressurized atmosphere will be retained in the modules during the untended periods between assembly phases.

Fire-Protection Principles

The designs for the Space Station *Freedom* fire protection follow the principles established for the Shuttle. Again, flammability testing will screen out many materials and components from use. The Fire Detection and Suppression subsystem (FDS) is a component of the Environmental Control and Life Support System (ECLSS). The key requirements for fire detection and suppression (H. Kolnsberg, Boeing, unpublished presentation, Nov. 1991) are summarized as

- independent FDS in each module or element,
- fire protection of untended locations without need for monitoring by onboard or ground personnel,
- data management system to provide a remote signal indicating a fire and fire location,
- automatic and manual means of fire suppression,
- nontoxic extinguishing agents compatible with the ECLSS, and
- single-failure-tolerant designs for the FDS.

These common-sense requirements have proven to be very difficult to meet, however, because of the severe limitations on mass, volume, and power in the station. The ability of current designs in achieving the desired goal of efficient FDS operation in the confined quarters of *Freedom* remains to be demonstrated.

Freedom Fire-Detection Designs

The interior of the cylindrical Space Station *Freedom* modules has a central core surrounded by banks of racks along the walls, ceiling, and floor for installation of equipment for experiments, flight monitoring, life support, and housekeeping (fig. 3). The basic configuration of a standard rack, constructed of graphite-epoxy composite materials, is illustrated in fig. 4. Powered racks, those with utilities and electricity, are to be protected with a smoke detector in the internal ventilating-air return collector and a solenoid-activated signal-flag alarm indicator. In the proposed *Freedom* smoke-detector, shown in concept in fig. 5, smoke particles in the air stream attenuate and scatter a laser beam. Radiation sensors in the detector provide an analog signal proportional to the smoke-particle concentration. Prototype smoke detectors are now being evaluated in *normal-gravity* tests for smoke response, mechanical characteristics, and electrical performance.

The single-point-failure tolerance specification stated in the preceding section implies the redundancy that, upon the failure of a primary system, protection will be retained through an equally reliable secondary system. Initial *Freedom* designs offered redundancy by duplicate photoelectric smoke and thermal detectors in each powered rack and additional smoke detectors in the common module air-supply ducting. Design simplifications, however, eliminated the thermal detectors (which are probably ineffective for early warning, anyhow) to save mass and eliminated the common ducting in favor of individual fans for distributed ventilation systems in each powered rack. New approaches to guarantee single-failure tolerance in the current ECLSS designs are still under consideration.

Fire detection in the central module core, in contrast to that in the powered racks, is provided by flame detectors, sensing radiation from overheating components or incipient flames. The proposed Space Station *Freedom* flame detectors incorporate three sensors in each unit, tuned to ultraviolet, visible, and infrared wavelength bands. Built-in test equipment in the form of internal light sources offer periodic operational checks. While this detector concept has the advantage of multiple-response logic from three signals to distinguish a potential fire from stray radiation, appropriate alarm set points are not yet established. These definitions require information on microgravity flame temperatures, spectral qualities, and their time variations.

Fig. 6 is a sketch of the end cone of the laboratory module, identifying several of the many components mounted on, or passing through, the end cone. The proposed flame detector is shown, installed for a line of sight into the central model core. Since a corresponding detector will be mounted on the opposite end cone, the two detectors, observing in effect the same volume, satisfy the single-failure-tolerant design requirement.

While the smoke and flame detectors discussed are the fire-detection systems currently specified for the *Freedom* MTC configuration, alternative concepts are under study. An obvious method of promise is the use of atmospheric gas sampling, already considered for ECLSS quality monitoring (ref. 16). The most sensitive indication of pyrolysis and combustion of almost all organic materials is carbon monoxide evolution, although effective sampling systems must be devised for improved response times if gas-sampling applications to fire detection are considered (ref. 13).

Freedom Fire-Suppression Designs

For the Space Station *Freedom*, the designated fire-suppression agent is carbon dioxide, which offers environmental and logistic advantages over the current Shuttle agent, Halon 1301. The selection of carbon dioxide is justified by the results of several system trade-off studies (summarized in ref. 8) and normal-gravity evaluations (ref. 17). The removal of excess carbon dioxide, at least in modest quantities, is within the capabilities of the Space Station *Freedom* ECLSS.

The *Freedom* fire-suppression designs must meet specified requirements (M. Gard, NASA Marshall, unpublished presentation, March 1992). Foremost among these are

- confirmation of a fire prior to automatic suppressant release,
- allowable CO_2 leakage to the general module to be no greater than a maximum concentration, to be specified,
- CO_2 supply in any module sufficient for at least two releases into the largest enclosed volume (powered rack),
- two portable fire extinguishers located in separate areas in each module,
- each portable fire extinguisher capable of extinguishing a fire in the largest enclosed volume, and
- inadvertent CO_2 release prevented by two-failure tolerant designs.

The proposed fire-suppression system, which is a derivative of the current Shuttle technology, consists of a combination of fixed and portable extinguishers. In brief, the logic, shown in a simplified representation in fig. 7, offers choices of no action, manual suppression, or automatic suppression in response to an apparent fire alarm. The automatic system is a centralized delivery system with remotely operated release valves at each powered rack. A conceptual sketch of the proposed system is shown in fig. 8. The portable fire extinguishers will be accessible at each end-cone location, as shown in fig. 6.

The *Freedom* fire-suppression system is sized to deliver suppressant to achieve a 50%-vol. concentration in the largest powered rack (with excess pressure venting as necessary) within one minute of agent release. The designers prefer to avoid two-phase flow in the delivery system; hence, the system is limited in capacity, because the carbon dioxide storage must be at less than the saturation pressure at ambient temperatures, *i.e.*, as a superheated gas (ref. 18).

Freedom Fire-Suppression Problems

It is evident that there are serious problems to be resolved in the design and operation of the *Freedom* fire-suppression system. The most important issues are

- non-conformity to the general requirements for the FDS,
- lack of commonality among international program partners, and
- prescribed agent that is unacceptable for use in the Hyperbaric Air Lock.

Despite the requirement limiting the maximum atmospheric leakage concentration of carbon dioxide, the designation of this agent as meeting the "nontoxic" requirement may be questioned. In addition, the redundancy for the single-failure-tolerance has not been achieved. Original design proposals called for backup suppression by venting the atmosphere to the vacuum of space. At present, the objections to venting are that the venting flow temporarily enhances the burning rate in microgravity (ref. 9), the final total pressure for guaranteed fire suppression is unknown, and the stores of makeup atmospheres for reconstitution after venting are limited.

The Space Station *Freedom* is an international program, with Japan and the European Space Agency (ESA) each contributing pressurized laboratory modules in the final space-station configuration. The international laboratories will be assembled after the MTC, but their development is now underway. The FDS designs for the international modules are derived independently of the corresponding U.S. subsystems, but the subsystems interconnect through common data-management systems and intermodule ventilation flows. All three international partners now agree on a carbon dioxide system for fire suppression, with many details equivalent in principle to those established for the U.S. modules. There are, however, some primary design and operational differences. Most of these variations do not affect safety, but one discrepancy is of concern. Because of possible system icing and limited pressure-relief capacity, the suppressant-flow system cannot deliver the required quantity of carbon dioxide in one minute in the ESA module. A maximum release-time specification of 30 minutes was requested, an unreasonable delay time for fire suppression in a closed environment. A compromise goal of 10-min delivery time is now under consideration, a delay that still is regarded as unsatisfactory by safety specialists.

The Hyperbaric Air Lock (HAL) is a chamber within one of the modules, sized to accommodate a patient and a medical attendant for treatment of decompression sickness and for other medical activities. While the HAL is not a component of the MTC assembly, its fire protection is actively under development. The HAL will have an atmosphere of 21% O_2 in nitrogen at a maximum total pressure of 340 kPa. If carbon dioxide is released to extinguish a fire in the HAL, the medical specialists fear that the resulting partial pressure of carbon dioxide at the proposed suppression concentration in the HAL will be highly toxic.

A recent communication (S. Pool, NASA Johnson, unpublished letter, April 1992) discussed alternative fire-prevention and suppression approaches for the HAL, although none of these are ready for development. The HAL proposal is to retain the common fire-detection system of the U.S. laboratory module, but to install a separate, dedicated fire-suppression system. The proposed fire-suppression concept includes nitrogen purging of electrical and instrument racks within the HAL for first-order fire prevention. Primary fire suppression will be furnished by a portable nitrogen extinguisher, which is a method that has no design counterpart in conventional fire-extinguisher technology. In addition, a fixed nitrogen-suppression system will release nitrogen to dilute the HAL atmosphere after extinguishment to prevent reignition.

CONCLUDING REMARKS

This paper discussed the features of fire protection incorporated into current and proposed U.S. human-crew spacecraft. In general, there is a strong reliance on preventive measures along with use of proven detection and suppression techniques. The experience with minor "near-fires" on Shuttle missions has shown that the crew response is the major factor in alleviating danger, but designed safety provisions offer an adequate backup.

For the future Space Station *Freedom*, dependence on human response will not be sufficient, and reliable automated fire protection is essential. The difficulties facing the *Freedom* environmental- and safety-design specialists must be appreciated. The principal drivers for the designs and operations are the stringent and sometimes conflicting (and often changing) specifications, to be met within the severe restrictions on material and component mass, volume, power, quality control, and cost. Certain alternatives, such as those for multiple-failure-tolerant features, await new inventions well beyond the present state-of-the-art. In addition, the fire-safety provisions must advance the goal of full utilization of *Freedom*, must allow for the long-duration conduct of a varied crew, and must satisfy the individual safety approaches of international partners tied into the common safety network.

While it would appear that microgravity combustion research plays a secondary role in spacecraft fire-protection strategies, effective and trustworthy fire protection can benefit greatly from fundamental scientific knowledge. The microgravity combustion research community has much to offer advanced spacecraft fire safety. Already spacecraft fire safety is guided by preliminary information on microgravity ventilation effects and radiant flame (non-flickering) characteristics. Examples of other important needs that may be addressed by microgravity combustion research are the assessment and prediction of material flammability, the physical and radiant characteristics of fires, gaseous and aerosol emissions from fires, the physical and chemical actions of extinguishment, and the long-duration toxic and corrosive effects of combustion and extinguishment products.

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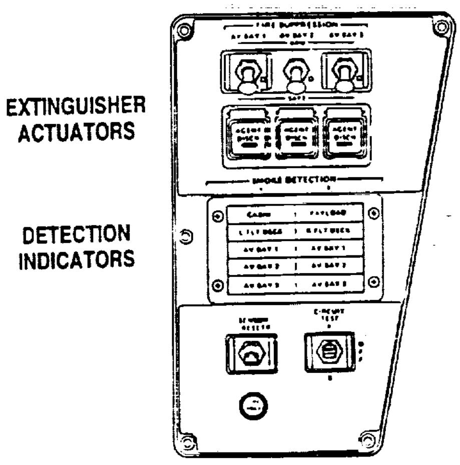

Figure 1. - Shuttle Fire Detection and Suppression Panel

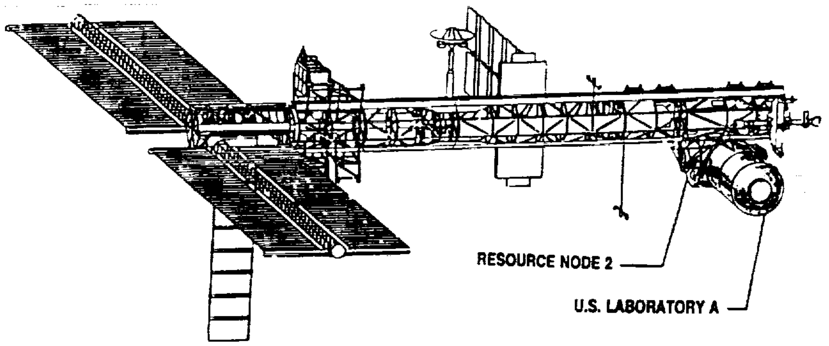

Figure 2. - Sketch of the Man-Tended Configuration of Space Station Freedom

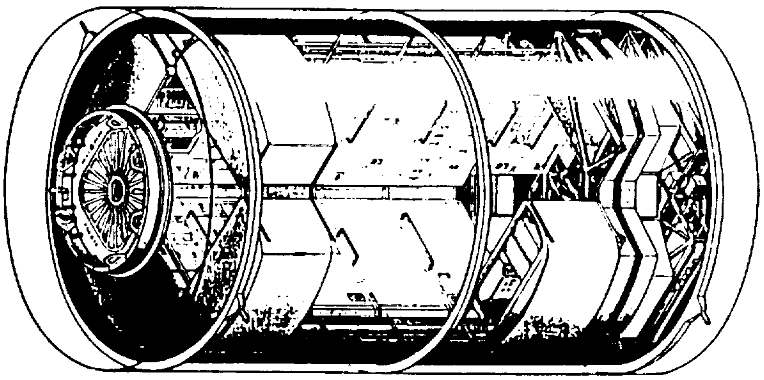

Figure 3. - Phantom view of the U.S. Laboratory Module for *Freedom*, showing central core and rack arrangement (Boeing design).

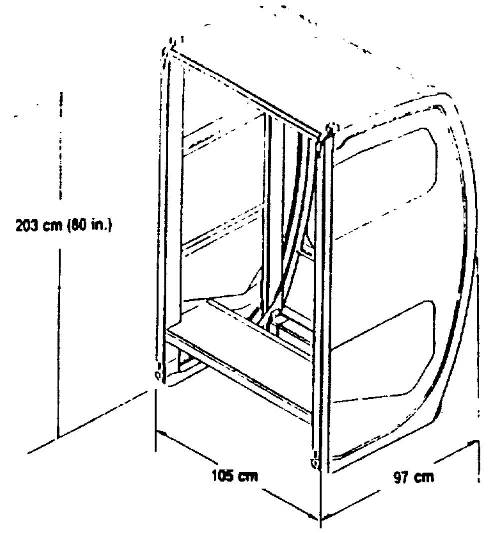

Figure 4. - Typical rack design for the Space Station *Freedom*.

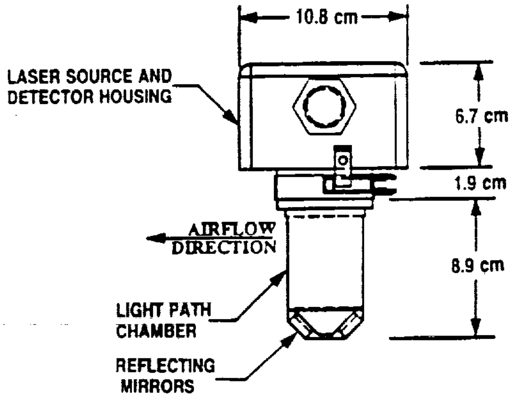

Figure 5. - Concept of photoelectric smoke detector proposed for *Freedom* racks (Allied Signal design).

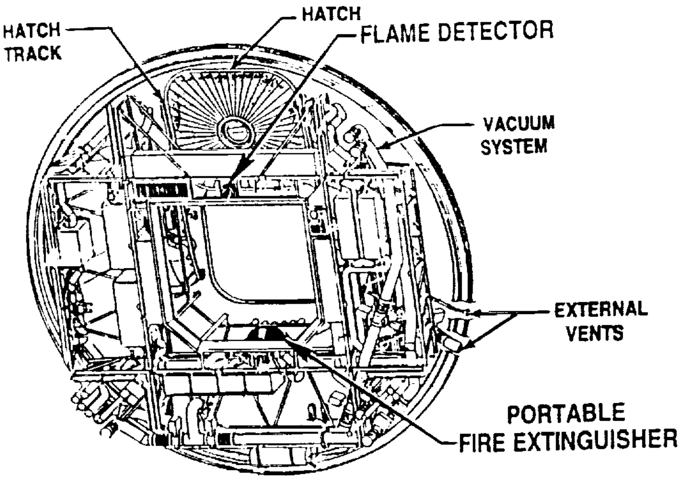

Figure 6. - End-cone arrangement of *Freedom* Laboratory Module

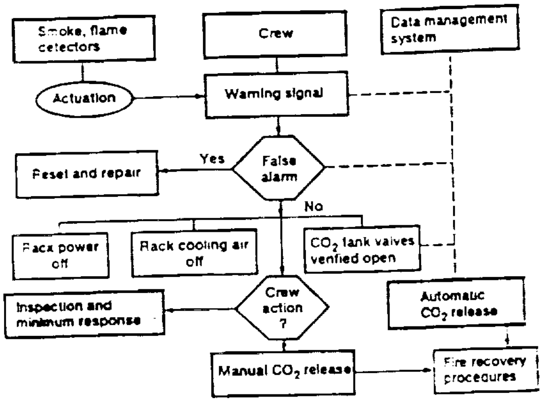

Figure 7. - Fire detection and suppression response logic for *Freedom*.

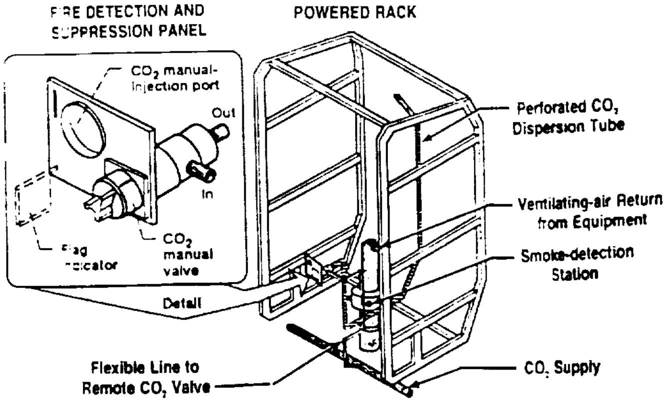

Figure 8. - Proposed Space Station *Freedom* carbon dioxide suppression system.

SESSION F - IGNITION, SMOLDER, AND FLAME SPREAD OF CONDENSED PHASE FUELS

(Chair, Raymond Friedman)