N88-12527

SPACE STATION INTERNAL ENVIRONMENTAL AND SAFETY CONCERNS

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Space stations of the future will have many areas of concern involving safety. The nature of the operation of space stations will require that safety be of paramount importance to ensure crew survivability and mission continuity. Space stations will be designed as outposts on a new frontier: space. This frontier is hazardous and unforgiving. Mistakes in the operation of a space station or the prediction of conditions and hazard scenarios could have very serious consequences. Space stations will have long lifetimes, limited capability for rescue, extremely hazardous operating environments, crewmembers who will not be astronauts, and a complex set of operating procedures. The possibility for mishaps to occur is very real.

SPACE STATION MODULES

Space stations will require some typical kinds of occupancies within their individual modules to be functional. The first basic kind of module that will be found is a habitation module. This module will contain the living space for the crew. The crewmembers will prepare and eat their meals in the habitation module. Facilities for personal hygiene and recreation and exercise will probably be found in the habitation module. Space to store the personal belongings of the crew and supplies necessary for dining will be found here.

A second kind of module occupancy that will be typically found in space stations is one or more laboratory modules. The purpose of space stations, the advancement of science and technology, will require extensive facilities to perform experiments of many types in the microgravity of space. As with laboratory facilities on earth, there will be hazardous processes and chemicals used in laboratories on space stations, and the probability for mishaps to occur is appreciable. Laboratories will require careful design and control to achieve safe operations.

A third kind of module that will likely be found on future space stations is a supply, or logistics, module. This module will be used to store consumables required for the operation of a space station. As with some storage facilities on earth, materials that are incompatible with each other may be stored side by side. The strict configuration control requirements for spacecraft will provide controls and safeguards for these types of storage, but the existence of incompatible materials near one another increases the probability of a mishap.

Figure 1 indicates a possible arrangement of the NASA Space Station modules. The modules in this figure are connected together by nodes and tunnels. Two of the modules are connected together in a circular arrangement, with the other two attached to this circular track.

Figure 2 is a possible arrangement of the inside cross section of one of the modules. Maximum advantage of space is used in this arrangement. The insides of the module next to the outer walls are used for the location of avionics, equipment, and storage areas. The habitable spaces are contained within a square cross section inside the module.

MODULE HAZARDS

Safety concerns in the internal environment fall into several broad categories. Radiation is more intense in the environment of space, in both its ionizing and nonionizing forms. Ionizing radiation will take the form of gamma rays, x-rays, and high-energy charged particles. Nonionizing radiation that will be found in the internal environment will probably consist of ultraviolet rays from viewing ports in the module hulls and beams from the experimental use of lasers in the laboratory modules.

Toxic substances will be used in the operating systems of the Space Station and in the laboratory experiments. The threat of an inadvertent release of a toxic gas, liquid, or solid will always be present. The effects of such a leak in a space station will be compounded by the nature of the Space Station's location and design. The Space Station will need real-time detection and analysis systems to detect the accidental release of toxic substances. Real-time analysis is needed to allow the crew to decide on a course of action to neutralize the leak.

Emergency decontamination apparatus will be needed for personnel working in laboratory modules. Emergency containment kits are available today for use in laboratories; this same type of approach could be adapted for use in a microgravity environment. Self-contained emergency shower devices and eyewash devices could also be developed for use on Space Station. Apparatus specifically tailored for decontamination of personnel exposed to particular substances could be provided on an as-needed basis.

Toxic chemicals in the internal atmosphere are not the only crew threat. Biological organisms and particulate matter in the internal atmosphere present health threats to the crew. In the microgravity of space, large particulate matter does not automatically fall to the floor of a compartment. Particulate matter of any size will follow the flow of the mechanical ventilation in a module. Particulates with diameters larger than 150 μm present an irritation problem to the crewmembers. Biological organisms will always be present. If they find internal atmospheric conditions suitable for growth, they can reach populations that present health threats to the crew. Control of the internal atmospheric humidity, temperature, food storage and disposal, and sterilization and filtering of the internal atmosphere will reduce the probability of illness due to biological organisms.

Crew injuries and illnesses are particularly serious matters due to the remoteness of the Space Station. Crew expertise and training to treat injuries and illnesses will be a necessity. Medical supplies will be necessary to handle anticipated problems.

Finally, there is the threat of fire or explosion. Fire or explosion will result in additional threats due to their aftereffects. Fire or explosion will do damage to the spacecraft system in which it occurs. Crew response is required to control the threat; this presents the threat of injury to the crew. After the fire or explosion threat has been controlled, there is the problem of internal atmospheric contaminants. Fire is perhaps one of the most credible threats, the most likely to occur. There are many aspects to this phenomenon which must be incorporated into the design of Space Station.

HISTORIC SPACECRAFT FIRE PROTECTION

There have been a variety of fire protection methodologies applied to U.S. manned spacecraft since the Mercury program. A clear and distinct pattern has not emerged.

The Mercury and Gemini spacecraft were very small in relation to the Space Shuttle Orbiter of today. The Mercury capsule contained one person; the Gemini capsule contained two persons. Fire detection on these spacecraft was accomplished via the sensory perception of the crew. There were no systems designed specifically for fire suppression, but the food rehydration gun on these spacecraft conceivably could have been used for this purpose had it been necessary.

The Apollo spacecraft was considerably larger than Mercury and Gemini. The Apollo Command and Service Module (CSM) accommodated a crew of three. After the ascent phase of the mission, the acceleration couches to which the astronauts were strapped could be folded up and out of the way. During the lunar landing missions the Apollo CSM was accompanied by the Lunar Module (LM). The LM could hold two persons.

Fire detection on the Apollo CSM and LM was again left to the sensory perception of the crew. There were no specific smoke detection schemes, although the possibility of using a condensation nuclei fire detection system was considered (ref. 128).

Fire suppression on the Apollo spacecraft was provided via several means. In The CSM, the primary means of fire suppression was a portable foam fire extinguisher. The food rehydration gun also had a flow-control spray nozzle and was utilized as a backup fire suppression system. In the Apollo Lunar Module, the fire suppression system was the food rehydration gun.

The use of strict materials flammability control requirements came into being during the Apollo era. The effects of oxygen-enriched atmospheres on the flammability of materials were then more fully understood.

The Skylab program was conducted in the early 1970's as an orbiting workshop. Skylab consisted of an upper stage of a Saturn booster rocket that had been converted for manned use in space. It had a docking adapter to which the Apollo CSM was berthed. Skylab was the first U.S. manned spacecraft that was too large to rely on the sensory perception of the crew for fire detection. Fire detection was accomplished by the use of line-of-sight ultraviolet-type fire detectors. Fire suppression on Skylab consisted of portable foam fire extinguishers. A schematic diagram of one of these portable fire extinguishers is shown in figure 3. These fire extinguishers had a removable nozzle so that the foam could be discharged through built-in openings in the avionics panels in the event of a fire in the avionics. Figure 4 (ref. 129) shows the locations of the portable fire extinguishers in Skylab and the estimated crew translation times.

The Space Shuttle Orbiter in use today can accommodate a crew of eight persons. The crew cabin consists of two areas of habitable space: the flight deck and the middeck.

Fire detection on the Space Shuttle Orbiter is provided by the use of ionization smoke detectors located in the crew cabin and the avionics bays. Figure 5 (ref. 130) shows the locations of these smoke detectors. These smoke detectors have a self-contained fan to draw cabin air into them for sensing purposes.

The Space Shuttle Orbiter uses portable and fixed Halon 1301 systems for fire suppression. The agent storage containers for both fixed and portable systems are similar, the difference being that the fixed systems are remotely discharged from a control panel on the flight deck. The fixed fire suppression systems on the Space Shuttle Orbiter are located in the three forward avionics bays. Figure 6 (ref. 130) shows the location of the portable fire extinguishers in the crew cabin. As was the case in Skylab, the nozzle on the portable fire extinguishers is compatible with fire ports (openings) in the panels. The agent nozzle can then be inserted into an opening in the instrument panels and the agent discharged to extinguish fire behind the instrument panels. The portable fire extinguishers can also be discharged through the openings in the avionics bays shown in figure 7 (ref. 130) in case the fixed fire suppression systems in the avionics bays fail.

MICROGRAVITY FIRE BEHAVIOR

The history of fire protection on manned U.S. spacecraft indicates that there has been no clear pattern of agreement on what is ideal. To preface a discussion of what is ideal for fire detection and suppression in a microgravity environment, it is necessary that the differences in fire behavior between normal and microgravity be discussed.

Combustion in a normal (one-g) environment is driven by convection due to gravity-inducted buoyancy. Hot smoke is driven up and away from a diffusion flame. In microgravity, there are minimal buoyancy forces; products of combustion are not forced away from the diffusion flame (ref. 131).

Under calm conditions in a microgravity environment, the spread of the flame front is slower than in normal gravity. Calm conditions are seldom encountered in the usual crew space in a spacecraft, however. Due to other life support considerations and the need to provide cooling air for electronic equipment, forced airflow is provided throughout the habitable space. This forced airflow will increase and define the direction of flame spread in a microgravity environment. Velocities of airflow exceeding some threshold value may even help prevent the occurrence of diffusion flames.

SPACE STATION MATERIALS ACCEPTANCE

Unlike facilities on Earth, control of all of the materials that are used for construction and that are placed in a manned spacecraft is a normal procedure. Each material in a manned spacecraft must meet current National Aeronautics and Space Administration (NASA) flammability criteria (ref. 4), or its use must be evaluated and judged to be acceptable by a controlling group of program managers.

Materials flammability control in Space Station will probably be accomplished by using standards similar to the current standard used for the Space Shuttle Orbiter. Although the criteria for materials flammability acceptance are too lengthy to discuss here, there are four basic tenets that apply. Materials are categorized by their use and placement in the spacecraft. More stringent requirements are levied on materials that are placed in the same environment as the crew. Materials are tested for flammability characteristics in the same atmosphere(s) which they will encounter in the spacecraft. Finally, materials are tested in their end-item configuration.

Some essential materials are not able to pass the current NASA flammability criteria. These materials include some clothing, various personal hygiene articles, paper, and food. Avoiding large concentrations of these materials through good housekeeping practices is one way of lowering the risk of fire in the spacecraft.

SPACECRAFT FIRE DETECTORS

Types

Fire detection on the Space Station could be accomplished in several ways. Ionization-type smoke detectors, such as are used on the Space Shuttle Orbiter, could be used for this purpose. These detectors react best to particles in the 0.1 to 0.3 μm diameter range (ref. 132). This size range of particles is produced by flaming combustion. Ionization-type smoke detectors tend not to react well to particles with diameters larger than 0.3 μm.

Photoelectric-type smoke detectors are another possibility. These detectors react best to particles larger than 0.3 μm (ref. 132).

A method of smoke detection using a condensation nuclei counter such as was considered during the Apollo program would be feasible on Space Station. The condensation-nuclei fire detector (CNFD) uses a Wilson Cloud Chamber in its operation. Smoke-laden air is drawn into the CNFD by a sampling pump and is passed through a device with water to provide close to 100 percent relative humidity in the air sample. The pressure in the chamber in which the sample is located is then suddenly reduced by a vacuum pump. The moisture in the then supersaturated air will condense on nuclei present in the air sample, such as particulates from smoke. In tests conducted by Bricker (ref. 133), the CNFD was found to be faster than either ionization or photoelectric smoke detectors. The CNFD reacted well to both visible flames and to smoke from smoldering plastics after the plastics smoke had been passed through a device to further pyrolize it into smaller particles.

The CNFD type of detection system is not immediately ready for use in a microgravity environment. The CNFD utilizes water in its operating system to humidify the air samples. This makes this detection method somewhat more difficult to use in a microgravity environment than other methods. There is also more maintenance involved in the CNFD operating system.

The internal atmosphere in Space Station will be kept as free from particulates as possible for various health and operating reasons. The concentration of particulates in the internal atmosphere will be monitored by the use of a particle counter. Since both smoldering and visible combustion produce high concentrations of particles, it may also be feasible in the Space Station to use a particle counting system for a smoke detection method.

Commercially available optical-type particle counters today can measure particles with diameters as small as 0.3 µm, much the same as photoelectric smoke detectors. Commercially available condensation-nuclei counters can measure particles as small as 0.01 µm. The condensation-nuclei particle counters use alcohol as their condensation fluid, however, so their use in a manned spacecraft presents a threat in itself.

With the threat of fire from a flammable liquid that may be used in a Space Station laboratory, the use of ultraviolet or infrared fire detectors must be considered. Both types of detectors are line of sight devices; that is, there must be a clear path between the fire and the detector. They both detect electromagnetic emissions from flames.

Ultraviolet fire detectors can be adversely affected by extraneous emissions of electromagnetic radiation close to the ultraviolet portion of the spectrum. These emissions can include x-rays and microwaves. Infrared fire detectors can be affected by heat-producing devices within a space station. Ovens with high-temperature heating elements and viewing ports may cause infrared fire detectors to alarm.

In line with previously mentioned safety concerns regarding chemical contamination, a real-time infrared atmospheric analysis device is a possibility for fire detection. This type of device would detect gases from combustion such as carbon monoxide, hydrogen fluoride, or hydrogen cyanide.

Detector Systems

Any detection scheme will do no good if it is not designed to be in the path of smoke transport from a fire. The lack of natural convection in the microgravity of space makes the location of the detector a critical factor in Space Station. A possible approach is to locate the smoke detection devices in the environmental control and life support system (ECLSS) air circulation ducts. Smoke or particulates generated by combustion would be carried by the forced airflow through a duct to the smoke detector. Care must be exercised in this arrangement to have smoke detection devices located so as to be able to easily locate the source of an alarm in ducts that are manifolded together. Manifolded ducts will require more detectors.

After the smoke detection method has been chosen for Space Station, the decision as to how its input/output operation will be configured must be made. The annunciation of the alarm must get the critical information to the crew as quickly as possible. This information should include the fact that a detector has gone into an alarm condition, the location of the actuated detector, and the spread of the fire or its products. The actuation of a smoke detector should be indicated by both audible and visual means in Space Station. Information concerning the alarm should be available via commands to an onboard computer system. Visible means should be provided within an individual module to easily locate any smoke detector that is in an alarm condition.

All fire detection devices respond to some fire signature. These include visible and invisible particles, combustion gases, infrared and ultraviolet spectra, heat, and pressure increase. Many of these signatures are also produced by controlled phenomena, however, making the task of detecting hazardous uncontrolled fire more difficult and subjecting fire detection systems to false or inadvertent alarms. The goal of a fire detection system is to indicate with a high degree of confidence that a fire has occurred. False alarms must be minimized to prevent loss of crew productivity and alertness. The goal can thus be achieved by choosing good initial detection thresholds for fire signatures and by having the capability to adjust the thresholds as operating conditions and experience indicate. Multiple, independent detection techniques are also needed to independently confirm the existence of hazardous fire conditions.

SPACE STATION FIRE SUPPRESSION

Fire suppression on Space Station is also not easily accomplished with just one method. To effectively cover credible fire scenarios, both fixed and portable fire suppression systems are needed on a space station.

Gaseous Extinguishants

Gaseous agent fire suppression systems may be designed for either total flooding of a module or flooding of equipment or storage racks within a module. In either case, overpressurization of a module may occur and must be considered in the design of a fire suppression system. Module overpressure venting may be required during fire suppression agent discharge.

Gaseous fire suppression agents are very easy to handle in the microgravity of space. Bromotrifluoromethane, or Halon 1301 as it is commonly called, is one very effective gaseous extinguishing agent. It chemically inhibits chemical chain reactions in the combustion process to extinguish fire. Concentrations required for extinguishment of fires in electrical components are in the range of 7 percent by volume (ref. 134).

The use of Halon 1301 would require the least amount of agent storage space and pressure among the various feasible gaseous agents. Halon 1301 can be stored at <4 MPa (600 psi). The use of Halon 1301 would require no immediate cleanup of the area or surfaces in contact with the Halon or fire.

Disadvantages of Halon 1301 include the toxicity and corrosiveness of its decomposition products and of the agent itself. Halon 1301 may be incompatible with certain elements of the ECLSS on a space station. The most effective method of agent removal after discharge would be module venting.

Carbon dioxide is another gaseous fire suppression agent that may be feasible. It extinguishes combustion by displacement of oxygen in the atmosphere. Concentrations of carbon dioxide in total flooding system applications for electrical hazards on earth require carbon dioxide concentrations of 50 percent (ref. 135). This represents more mass that must be carried into orbit. Atmospheres of this composition are fatal to humans.

The use of carbon dioxide on a fire would also require no cleanup of the area contacted by the extinguishant. Carbon dioxide discharging onto equipment would present a low-temperature thermal shock to the equipment being impinged upon. Storage pressures of carbon dioxide are higher than Halon 1301. Carbon dioxide is stored in gaseous and liquid form on earth at pressures up to 6 MPa (900 psi).

Removal of carbon dioxide after discharge would first require partial venting of the module. After the module has been partially vented, the residual carbon dioxide could be removed by the carbon dioxide separation capability of the ECLSS. Although small concentrations of carbon dioxide could be removed by the ECLSS, high concentrations occurring in a short time may be a potential problem with the carbon dioxide separation capability of the ECLSS.

The use of carbon dioxide to flood equipment racks appears to be more possible than a total flooding system for a module. The amount of module venting required to prevent overpressurization would be less. The impact to the ECLSS would also not be as significant.

Nitrogen is another inerting gas that may be used as a fire suppression agent. It has the same basic extinguishing characteristics and problems as carbon dioxide. If module venting upon discharge of the nitrogen is used to prevent overpressure conditions, the concentrations required for fire suppression would be fatal to humans within the design discharge volume.

Removal of nitrogen after its discharge would again require partial venting of a module, with oxygen being added after the partial venting to restore the normal atmospheric composition.

Use of fixed gaseous fire suppression systems for flooding equipment and storage racks in a module would require a lower quantity of suppression agent than a total flooding system for a module. This method would also reduce the risk of asphyxiation to crewmembers, as it is not likely that persons would be present inside a storage or equipment rack.

There are also disadvantages to the flooding of equipment and storage racks with gaseous agents. An extensive agent piping network would be required. The location of the individual rack in which the fire had occurred must be known. If rack flooding is used, means must be developed to prevent the mixing and subsequent dilution of the gaseous suppression agent with module air from outside the rack. The forced airflow through the rack must be stopped and the rack must be sealed from the module prior to agent discharge. Sealing the racks prior to agent discharge would also help reduce the spread of products of combustion.

Portable fire extinguishers could be used within the habitable space for fire suppression. These portable fire extinguishers could use the same gaseous agents as the fixed fire suppression systems. Removal of the fire suppression agent after discharge from a portable extinguisher would be somewhat simpler due to the lesser quantities. Removal of Halon 1301 would still have to be accomplished by venting the module to vacuum.

Consideration must be given to the reaction force that would occur due to discharge of the agent from a portable fire extinguisher. The reaction force from a fire extinguisher using Halon 1301 would be less than that of an extinguisher using carbon dioxide or nitrogen because of the lower agent storage pressure.

Although use of each of the aforementioned gaseous fire suppression agents requires at least some venting of a module, operational procedures after the occurrence of a fire may also dictate that the module atmosphere be vented to vacuum due to the products of combustion alone.

Gaseous fire suppression agents are successful to varying degrees in extinguishing fire in ordinary cellulosic or solid nonmetallic materials. Halon 1301 is the most effective gaseous fire suppression agent of the ones mentioned for use on fires in ordinary combustible materials, but it requires higher concentrations and longer time in contact with the combustion area to be effective. Carbon dioxide and nitrogen are less effective than Halon 1301 for extinguishing fires in ordinary combustible materials. Fire extinguishers on earth using gaseous agents are designed mainly for use on flammable liquids and energized electrical equipment fires.

Water and Foam

Since gaseous fire suppression agents are not effective in the extinguishment of fires in ordinary combustible materials, the use of a backup fire-suppression system using water or water-based foam should be considered on Space Station. Such a system could take the form of either a portable extinguisher or a hose and flow control nozzle connected to the onboard water supply. A system using a foam agent would be effective on both flaming and surface combustion. Foam would adhere to the surface on which it was placed. Cleanup procedures would involve wiping the foam from the area of application.

The use of water in a fire suppression system would be feasible if a means to prevent the introduction of large amounts of free-floating water in a space station were developed. This could be done by having a sponge applicator on the end of the water hose or the use of a rigid containment box that could be placed over the fire area and into which the water would then be discharged.

Complete Venting

As a last resort, venting a module to the vacuum of space as a means of fire extinguishment could be used. The depressurization rate would be a consideration to prevent violent rupture of closed containers. Venting would also increase the rate of flame spread of the fire. The possibility exists that if the fire were near the outlet for venting a module, the flame would follow the venting gases and damage the venting out piping and valve(s). Repressurization of the affected module may not be possible after the venting operation.

FIRE SAFETY IN HYPERBARIC CHAMBERS

Space stations may have hyperbaric chambers for use in treating various types of decompression sickness that may occur during crew extravehicular activity (EVA). Capability to provide up to 600 kPa (6 atm) of pressure with varing percentages of oxygen, including some that are oxygen-enriched with respect to normal atmospheric composition, may be required from a medical standpoint. Fire detection and suppression systems specifically designed for an oxygen-enriched environment will have to be provided for a hyperbaric chamber on Space Station. Fire detection could be either smoke or flame either smoke or flame detectors. Flame detectors of either the ultraviolet or infrared type would provide the fastest response.

Fire suppression in an oxygen-enriched environment is a more complicated matter than the choice of detection methods. Of great importance is the fact that the occupants of the chamber cannot easily leave the confines of the chamber. The fire suppression agent chosen must be nontoxic and minimize the production of toxic decomposition products. Halon 1301 has been tested for use in an oxygen-enriched environment by Kimzey (NASA Manned Spacecraft Center Internal Note, Oct. 1967). He concluded that Halon 1301 is not effective for extinguishing fire in pure oxygen atmospheres. Halon 1301 in other oxygen-enriched atmospheres must be carefully evaluated for effectiveness and toxicity due to decomposition byproducts and concentrations required for fire extinguishment.

The use of carbon dioxide for a fire-suppression agent would present an asphyxiation hazard to the chamber occupants. Nitrogen could be added without displacing the existing oxygen for fire-suppression purposes. Water would also be feasible for use as a fire-suppression agent in a hyperbaric chamber in a microgravity environment. A system such as this would utilize a dedicated water supply tank containing water at a pressure sufficiently higher than the hyperbaric chamber so that an effective spray pattern could be achieved from the discharge nozzles. The discharge nozzles would be designed for three-dimensional impingement. Water flow densities could be based on requirements for oxygen-enriched atmospheres at normal-gravity conditions. Cleanup and containment equipment and procedures would be necessary for a fire suppression system using water.

FIRE CONTROL PROCEDURES

After the fire detection and suppression systems have been designed and built and Space Station is operational, the problem of "what to do when fire occurs" becomes one for humans to solve. A Space Station crew will have to be thoroughly trained to cope with fire emergencies.

After a fire has been detected, adequate means must be provided to alert the crew that a fire is in progress. The crew must then be able to interpret signals from the fire detection system to locate the fire quickly. Upon locating the fire, the crew must have a good idea of what the fire involves and how much of a threat it appears to be. The crew must perform tasks such as donning emergency air breathing apparatus, shutting off airflow to the affected equipment, and disconnecting electrical power to the affected equipment if deemed appropriate. The method of extinguishment must be decided upon. Should a fixed or portable gaseous agent system be used? Perhaps a water-based system would be better. The agent must then be effectively applied. After the fire has been extinguished, the fire area and its effects must be cleaned up. Finally, normal operations must be restored.

The tasks required to completely handle a fire on earth are usually done by several different entities. In Space Station, the crew will have to handle all of the tasks involved; their lives will depend on it.

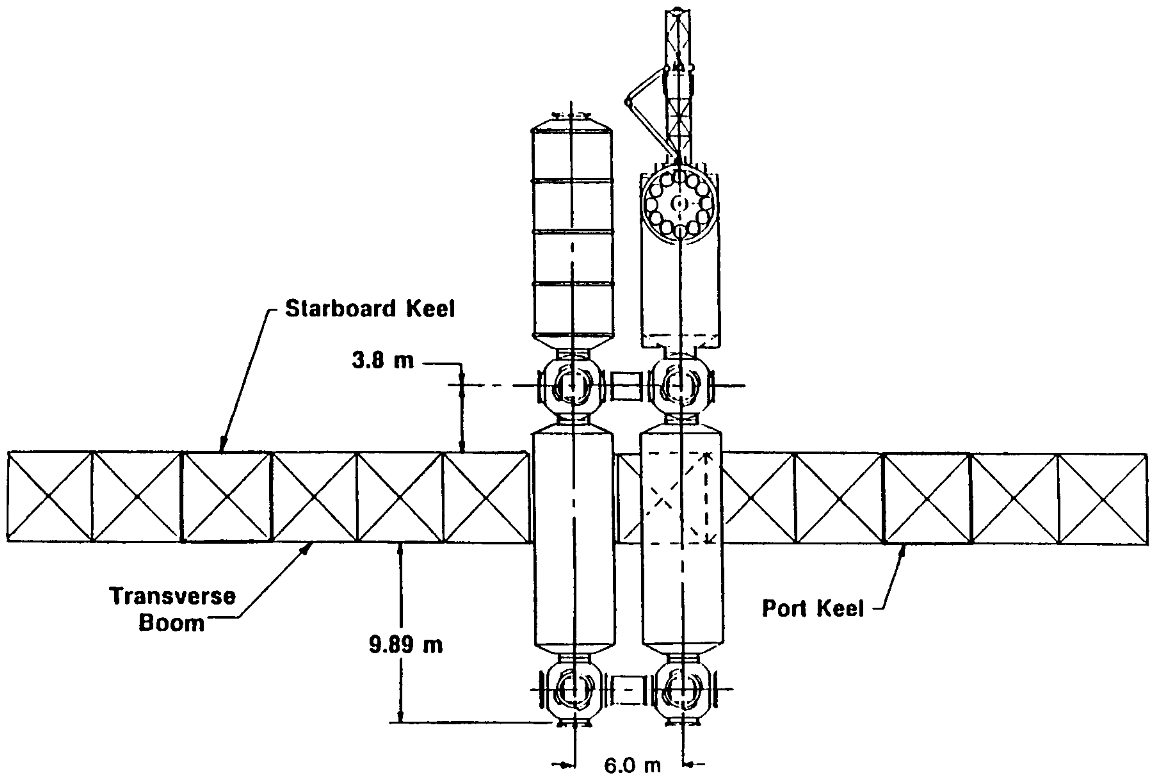


Figure 1. - Sketch of Space Station module arrangement.

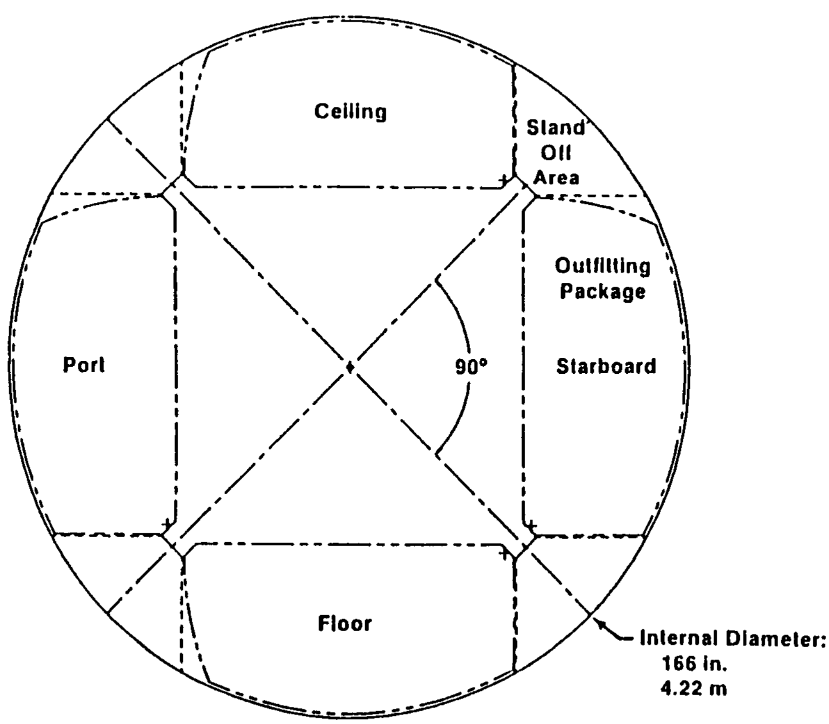


Figure 2. - Interior space in Space Station module.

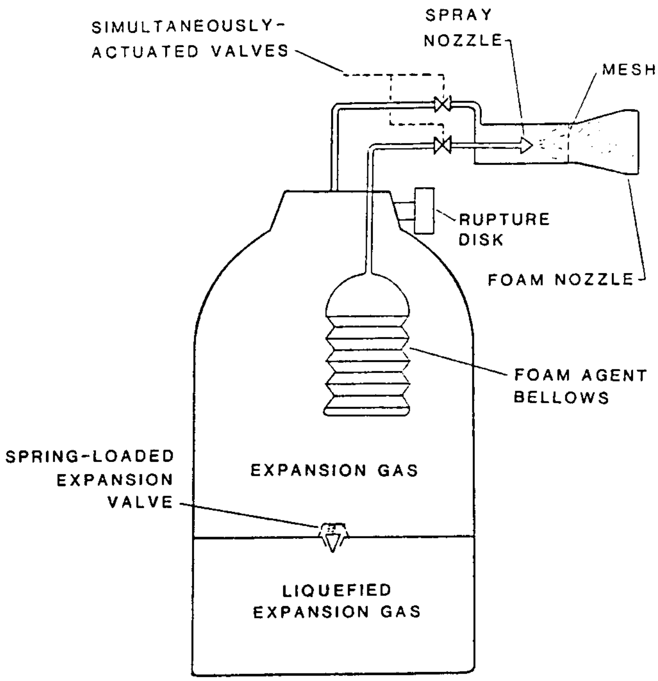


Figure 3. - Skylab fire extinguisher.

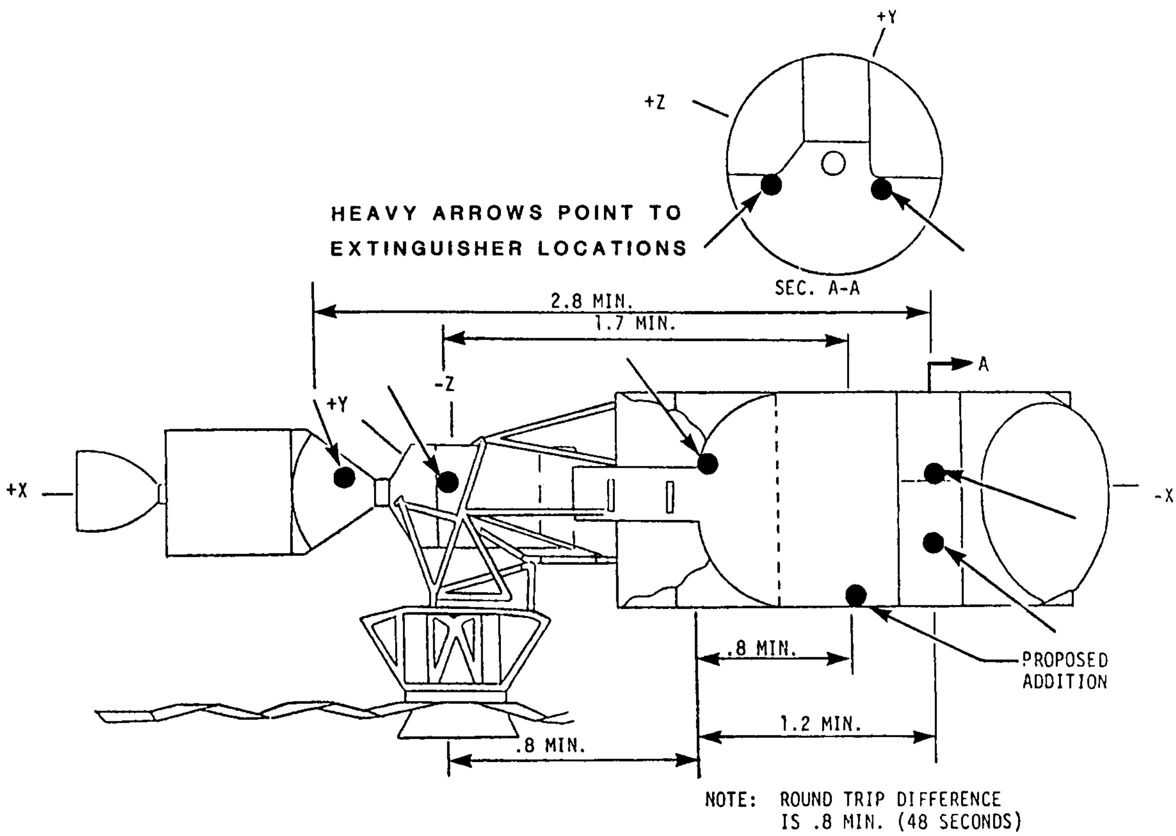


Figure 4. - Skylab fire extinguisher locations and estimated crew translation times.

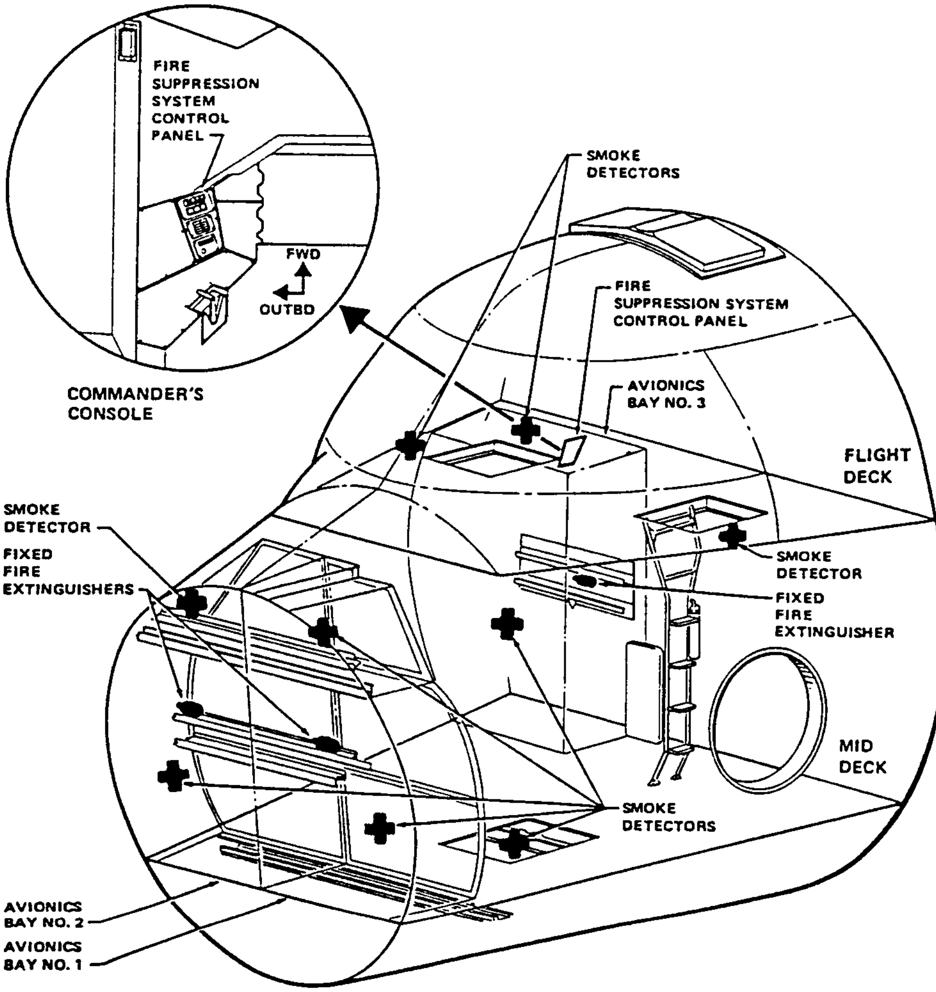


Figure 5. - Shuttle crew cabin and avionics bay fire protection.

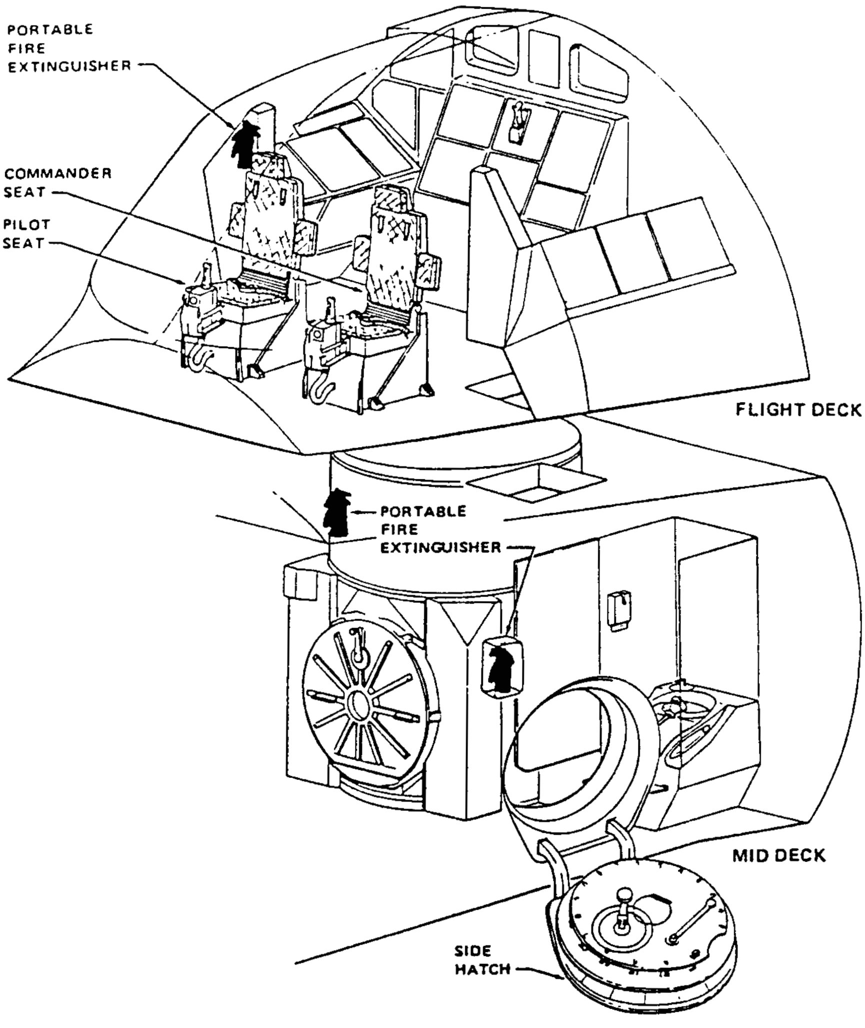
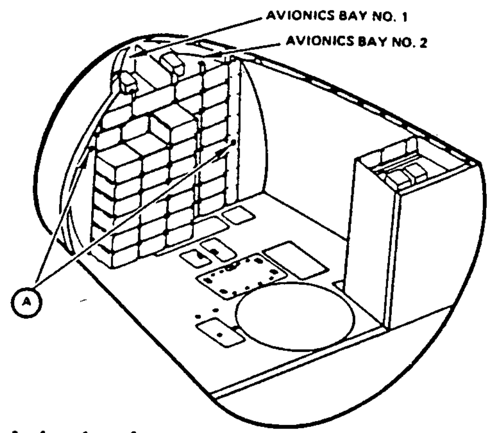


Figure 6. - Shuttle portable fire extinguishers.

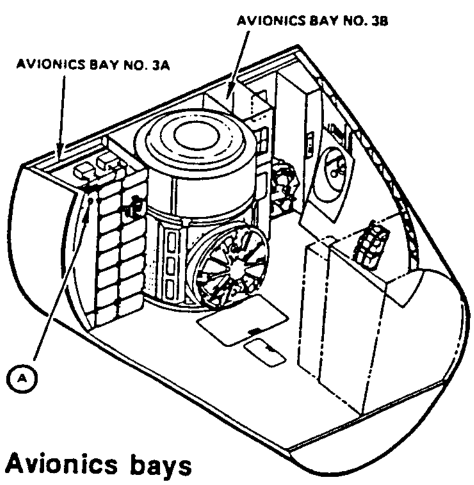


Avionics bays no. 1 and no. 2

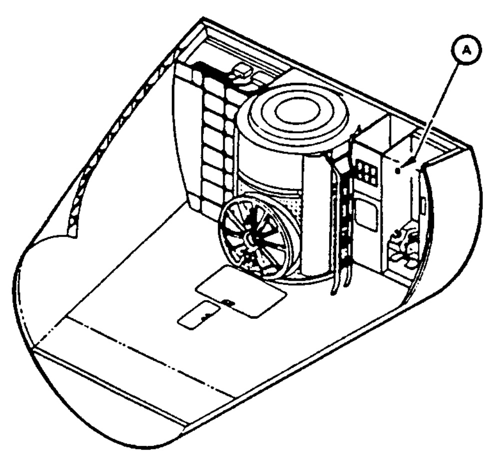
Note

- FIRE PORTS PROVIDE ACCESS TO AVIONICS BAYS
- FIRE PORTS SIZED TO FIT PORTABLE FIRE EXTINGUISHER NOZZLE

(A) FIRE PORT/GUIDE (TYPICAL)



Avionics bays no. 3A and no. 3B



Personal hygiene station

Figure 7. - Fire extinguisher ports in the Shuttle cabin.