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Life Support System Considerations for Space Station

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ABSTRACT

With the growing desire to initiate a Space Station program, the interest in advanced, regenerative life support systems is also increasing. This paper briefly reviews this future spacecraft and concentrates on the advanced technology in some of the key functions of life support for this application. This paper reviews the basics of life support and its importance within a space station program. It concentrates on the impact of major requirements and discusses some of the key influences that impact the design of the system. It also projects some of the key functional areas of the life support system which are most likely to be implemented from today's current technology.

The imminent availability of the Space Shuttle has rekindled interest in the longer duration space missions and permanent orbiting space platforms. Studies are underway to define missions and concept the orbiting facilities based on the capabilities available with and limitations imposed by the Space Transportation System. A work base in space is required to economically perform the long duration, complex missions of the future and to utilize the Space Shuttle in its intended role as a space truck. The term "Space Station" is again coming into vogue, although other titles for this program are currently in use.

Current activities are directed at two potential approaches to deploying an operational Space Station. The first approach has been under study for well over a year by the Boeing Company for NASA/Johnson Space Center. This conceptual study is entitled "Space Operations Center" (SOC). It is aimed at establishing an initial minimal operational capability before 1990 and modularly growing this facility to a full-fledged Space Station. The SOC (Figure 1) capability would include:

- Assembly and checkout of large orbiting systems in space.
- On-orbit assembly, launch, recovery, and servicing of space vehicles.
- Tending of co-orbiting, free-flying satellites.
- Accommodation of science and applications experiment programs.
- Permanent manned operations capability in space with reduced dependence on earth for control and resupply.

Since this SOC study represents the most up-to-date analysis of a Space Station, it provides much of the framework for the information presented in this paper.

The second study being pursued by NASA Marshall Space Flight Center is entitled "Manned Space Platform" (MSP). This study is being performed by the McDonnell Douglas Astronautics Company and is aimed at evolving a manned Space Station starting with an orbiting Power System (or module). This power module initially provides electrical power, heat rejection, and data management services to attached payloads including the Space Shuttle Orbiter and its payload complement (Spacelab, etc.). Later, the power module would be expanded with a structural adapter to provide additional payload docking ports and increased service capability. This combination of space structures is currently referred to by NASA as the "Space Platform". Subsequently, one or more habitability modules would be added to this evolving assemblage to form the initial MSP (Figure 2). From this early MSP, it would eventually be grown into a full-fledged Space Station.

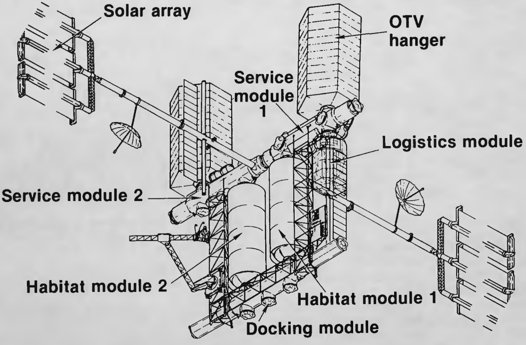

Figure 1. Representative space station configuration (based on space operations center study)

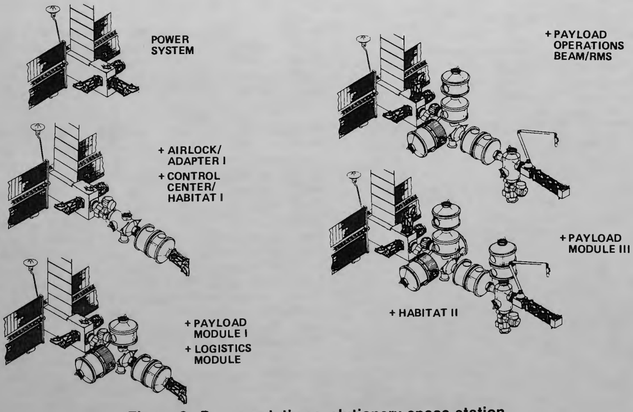

Figure 2. Representative evolutionary space station (based on manned space platform study)

The basic services and support functions provided by the above described Space Station versions are similar. Common among all of these services and support functions is the involvement of man. Man's presence is mandatory in any of these activities since none are truly routine or totally repetitive. Consequently, any and all aspects of these future major space activities will require life support systems.

Life support equipment changes in concept application only as mission duration and/or crew size changes. It is relatively independent of the vehicle concept itself, but selection of specific life support equipment concepts is influenced by the type of power source being used to service the spacecraft. Consequently, as the basic Space Station grows and its services and functions increase, the life support equipment will evolve with it.

All of the Space Station concepts currently being investigated have much in common. They must all be transported to orbit and be logistically supported by the Space Shuttle Orbiter. The Orbiter has a 4.6 m dia. x 18.3 m long (15 ft. dia. x 60 ft. long) cargo bay which limits the design size and configuration of the modules that may be used to assemble the Space Station. Consequently, the habitability module which will contain man and, thus the life support equipment, will likely be very similar for any Space Station. The habitability module, therefore, may either be a new module design or a derivative of the current European developed Spacelab Module.

This paper investigates some of the major requirements which will influence the type of life support concepts adaptable to the Space Station missions. It briefly covers the key subsystem concepts currently available for use on this spacecraft. And it projects some of the key life support subsystem concepts. This paper does not try to solve problems or resolve issues, but rather it presents the key issues and alternatives to be considered in the selection and implementation of life support equipment for a Space Station.

LIFE SUPPORT

Man is both a delicate and demanding resource, but as history has demonstrated, a necessary ingredient in the accomplishment of nearly any task or mission. Man can only survive in a relatively narrow range of environmental conditions and in space, he consumes and uses large quantities of scarce materials while generating various waste products which must be removed to maintain a healthy and safe environment for his existence. Figure 3 illustrates the specific areas of man's basic needs. On Earth, most of these needs are adequately controlled, supplied, and/or managed by the natural ecological process. But in space, at least at this point in our technology development, they must be provided by life support equipment (physical and chemical processes). In addition, the absence of significant gravitational forces in space requires that many of these processes be much more complex. As an example, on earth natural convection assists in removing and transporting man's waste heat and generated toxic gases away from his immediate presence, but in space, forced ventilation must be provided to ensure man's health and safety.

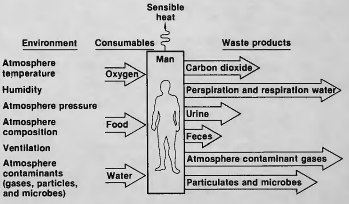

Figure 3. Man's basic life support needs

In addition to the direct support of man (which accounts for approximately twenty of the major life support functions required), his support needs in the areas of health, hygiene, safety and task performance requires nearly thirty more life support system functions. These additional functions include the consideration of minimizing logistics support, incorporating redundance and emergency provisions, and providing the necessary amenities for the well being of man on long duration missions. Table 1 lists most of the significant life support functions. This listing is categorized by the major service provided in the support system. Most of the work done to date on advanced, long duration space missions has shown that life support is one of the most complex and thermally demanding systems to be incorporated in these future spacecraft. Consequently, since the life support system is one of the major influences on the design of the thermal control subsystem, it is a necessary and integral part of the life support system.

The importance of Life Support to the future Space Station program can best be illustrated by looking at some statistics from the Space Operations Center (SOC) study performed by the Boeing Company for NASA (Reference 3). Considering only the Habitability Module (the primary occupation volume for man on this spacecraft), the life support system represents around 35 percent of the module weight, it utilizes over 16 percent of the total module volume, and it requires over 35 percent of the total module cost. Looking at it from the total SOC program standpoint, the life support system uses nearly 14 percent of the total heat rejection capacity, consumes nearly 25 percent (on the dark side of the orbit) and nearly 38 percent (on the sunlight side) of the total SOC power generated, and it requires around 20 percent of the total SOC funding. Consequently, Life Support is an important element of the future Space Station.

Table 1. Life support system functions

MAJOR LIFE SUPPORT FUNCTION	TYPICAL EQUIPMENT, PROCESS, OR FUNCTION REQUIRED
Environmental Control	
Atmosphere temperature control	Heat exchanger (HX)
Humidity control	Condensing HX and condensate collector
Atmosphere pressure control	Sensors and valves
Atmosphere composition control	Sensors and valves
Ventilation	Fans and distribution ducts
Atmosphere monitoring	Sensors and display
Vehicle leakage compensation	Sensors and valves
Vehicle wall temperature control and heat leak compensation	Insulation or active thermal conditioning
Atmosphere Revitalization	
Oxygen supply	Storage tanks or electrolysis of H_2O
Atmosphere diluent supply	Storage tanks or generation from chemical storage
Carbon dioxide removal and management	Chemical or regenerable process
Atmosphere contaminant gas removal	Catalytic oxidizer and/or physical /chemical process
Atmosphere particle and debris removal	Debris trap and filters
Atmosphere microbial removal or control	Filters or thermal process
Odor removal or control	Physical, chemical or thermal process
Water Management	
Water storage and/or reclamation	Tanks or water reclamation process
Water distribution	Valves and plumbing
Water thermal conditioning	Heater and chiller
Water purification or quality maintenance	Chemical additives or ion generator
Water quality monitoring	Sensors, display and valves
Wastewater storage or management	Tanks and valves
Waste Management	
Urine collection and management	Urine collector and tank
Fecal collection and management	Fecal collector and storage
Trash collection and management	Compactor
Food and microbe prone waste collection and management	Compactor or disposal and chemical additives
Food Service	
Food supply and storage	Storage bins, refrigerator, and freezer
Food preparation	Oven, counter, pots/pans
Food serving utensils and containers	Trays, knives, forks, spoons
Water dispenser (hot and cold)	Water dispenser
Thermal Control	
Heat collection and transport	Pumps, heat exchangers, plumbing, valves
Cold plate cooling	Cold plate heat exchangers
Heat rejection	Radiators
Health and Hygiene	
Personal hygiene	Full body shower, hand wash
Housekeeping	Vacuum cleaner
Clothes management and cleaning	Clothes storage and clothes washer
Dish cleaning	Dish washer
Medical provisions	First aid kit and drug storage
Exercise provisions	Stationary bicycle, treadmill
Recreation provisions	Games, books, television
Habitability, operations and safety	
Furniture and bedding	Desk, table, chairs, beds
Fire control	Sensor, warning, extinguishing equipment
Lighting	General lighting and portable spot lighting
Emergency shelter and life support provisions	Isolatable volume or redundant habitat
Protective garment and life support provisions	Intravehicular pressure garment
Emergency escape provisions	Portable enclosure for extravehicular transport
Life support system control and monitoring	Life support control center
Noise control	Noise suppressors
Privacy provisions	Curtains and/or partitions
Extravehicular Activities (EVA)	
Space suit	Pressurized mobility unit or garment
Portable life support provisions	Small, short duration life support system
EVA equipment servicing and recharge	Storage, recharge, cleaning and repair provisions

REQUIREMENTS

The major requirements and influences expected to be imposed on the life support system for the various versions of Space Station being investigated are presented in Table 2. The impact of these requirements are briefly discussed in the following paragraphs along with highlights of major influencing factors.

Vehicle Configuration - It has been established that a Space Station will be an assemblage of modules and structures, each limited in size and configuration by the Space Shuttle Orbiter cargo bay dimensions. Consequently, one or more of these modules will be devoted to crew habitation and this is where the majority of the life support subsystems and equipment will be located. Two or more habitability modules are desired to provide degraded mode capability and emergency shelter provisions for operation without a standby rescue vehicle. This will inherently provide complete on-orbit redundancy of all of the critical elements of the life support system.

Some of the life support subsystems may, more desireably, be located in a logistic module for ease of maintenance and service. One such element is the zero-gravity toilet since on-orbit repair, servicing and cleaning of this subsystem is a less than desireable task and potentially a health problem. Additionally, the significant volume and much of the weight elements of the toilet are in the storage container anyway, so that transportation back and forth to Earth of the entire unit may not impose much of a penalty.

Other life support subsystems which will likely have low duty cycles such as a zero-gravity whole body shower or clothes washer may want to be centrally located in order to service the crews from multiple habitability modules. This central location would be the core or interconnecting tunnel module which in the SOC study was referred to as the Service Module(s).

Another consideration relating to the vehicle configuration is the storage of degradables such as food. It would be desireable to distribute the food throughout the different pressurized modules of the spacecraft in order to avoid the loss of all or major portions of the stored food in the event of a failure in any single module. However, resupply considerations, health hazards and the crew's activities may argue for maintaining the bulk of the food storage in the logistics module while distributing emergency, nonperishable foods throughout the spacecraft.

Table 2. Major requirements influencing life support

Major Requirements \ Space Facility	Shuttle Tended	Early Base	Growth Base	Permanent Space Facility
Vehicle configuration (habitability related)	Single habitability module	Single habitability module plus	Multi-habitability modules	Multi-habitability modules or large volume facility
Mission duration				
• Design life	5 Years	10 to 20 years	20 Years	Permanent
• Manned operation	Up to 30 days	Semi-continuous	Continuous	Continuous
Resupply frequency	At visitations	30 to 90 days	90 days	90 to 180 days
Launch and resupply vehicle	Shuttle orbiter	Shuttle orbiter	Enhanced shuttle orbiter	New shuttle vehicle
Crew size	2 to 4	3 to 6	8 to 12	20 to 100
Power supply				
• Generator type	Solar	Solar	Solar	Solar or nuclear
• Power output	10 to 40 kW	40 to 50 kW	50 to 250 kW	250 and over kW
• Power type	115 Vac 28 Vdc	115 Vac 28 Vdc	115 Vac 28 Vdc	100 Vdc
Cabin total pressure	570 to 760 mm Hg	410 to 760 mm Hg	410 to 760 mm Hg	520 to 760 mm Hg
CO_2 partial pressure	3 to 4 mm Hg	3 to 4 mm Hg	2 to 4 mm Hg (max)	1 to 2 mm Hg (max)
Food type	Dry	Dry	Mostly dry and frozen, some wet	Wet, dry and frozen
Solid waste management	Compacted and stored	Compacted and stored	Compacted and stored	Decomposed or recycled
EVA frequency	Low	Medium	Medium to high	High
Emergency provisions	Shuttle orbiter	Shuttle orbiter and redundancy	Two or more habitability modules	Full backup and redundancy

Habitability and human factors considerations are two other areas influenced by the vehicle layout and configuration. Some amenities must be provided for man's well being. Significant space should be provided for food preparation, health maintenance, and recreation on long duration missions.

Mission Duration - This is one of the most important requirements in the selection and design of a life support system. Man's needs are a direct function of mission duration. And it is desireable to minimize the demands placed on the Space Transportation System as a resupply service supporting the Space Station crew. Consequently, as mission durations increase, the penalties (weight, volume, crew time and economics) for use of expendables and/or consumables becomes prohibitive. Conservation through recycling of items and regeneration of supplies becomes a necessity within the life support design. Exceptions to recycling, which are currently being investigated, are the scavenging of excess materials (such as oxygen) from the Orbiter and/or the Shuttle external tank and the use of boil-off from the on-orbit cryogenic tank farm (used to refuel Orbital Transfer Vehicles) for provisioning the Space Station.

Long duration missions also demand that the design provide for maintenance of virtually all subsystems and equipment in order to achieve the desired operational life. This includes adequate spares and maintenance provisions.

Resupply Frequency - This is the time span between required or planned visitations of the Shuttle Orbiter to the Space Station when provisions, crew exchange, and resupply would occur. The duration between these visits is generally viewed in the same manner as mission duration on a Shuttle Orbiter type spacecraft for consideration of life support penalties and alternatives.

Total resupply requirements over the full operational life of the Orbital Work Base are also influential in these considerations.

Crew Size - Life support sizing is also a direct function of crew size. With the modular configuration of the Space Station, the crew-size will be established initially at some fixed level which will set the life support size. Growth in crew size will be accommodated by the addition of more habitability modules, each with its own fixed capacity life support system. However, since each habitability module must be capable of providing emergency shelter for the crew of another module, the life support system size in each module must be able to accommodate the additional contingency but likely at some relaxed specification conditions. Also, as the Space Station grows beyond two habitability modules, the displaced crew may more desireably be distributed evenly among the remaining operational modules during an emergency situation and thus place less demand on the life support systems in any one module.

Power Supply - The availability of relatively low-penalty power from solar energy conversion on a Space Station will enhance the attractiveness of regenerative life support processes. It will provide a significant influence on the type of concept selected for each subsystem area. Some of the regenerable life support subsystem concepts such as carbon dioxide removal with physical/chemical processes are cyclical in their operation and use of electric power. Consequently, these subsystems can be designed to beneficially operate at peak power coincident with the orbital sunlight period. Other high power-using subsystems (such as water electrolysis) may also take advantage of the benefits of sunlight-only operation through oversizing of the equipment and the addition of accumulators or a large cabin volume which would damp-out the over-and under-needed production rates.

The use of regenerative fuel cells in place of batteries in conjunction with solar cells could change the benefits of designing for sunlight-only operation. However, the use of regenerative fuel cells along with the materials scavaging concepts noted under Mission Duration previously could have a significant impact on the life support system design and subsystems concept selection.

Voltage level is another parameter which could impact the design of life support equipment. Current spacecraft hardware designs are based on the use of either 28V dc or 400 Hz, 115V, three phase power. In order to minimize dc to ac conversion losses and still provide the benefits of high voltage, NASA has been pursuing the application of high voltage, direct current (>100 Vdc) technology to space. Although this technology is well along in development, the economics associated with its implementation are not likely to prove beneficial in time for application on the Space Station. The application of proven technology and existing designs is a major factor influencing development costs.

Cabin total Pressure - Selection of the cabin pressure level is a continuing issue between the life sciences community (who prefer earth-like conditions for their experiments) and the operations faction (who prefer practical pressure levels which are adequate for the mission to be performed). The Space Station is another target for this never-ending battle. It is the author's opinion that the operations people will win and that the cabin total pressure level will end up being between 410 mm Hg (8 psia) and 620 mm Hg (12 psia) since it is, as most of its various current titles implies, a "work" facility. This position is supported by looking at the relatively high extravehicular activity that is anticipated for the Space Station and the current technology level of anthopomorphic cloth space suits. The technology level of practical cloth space suits is currently limited to the range of 258 mm Hg (5 psia) to 310 mm Hg (6 psia). And considering the "Bends" problem which occurs at approximately a 1.6 to 1 ratio of cabin N_2 partial pressure to space suit total pressure, this leads to the projected cabin total pressure level. Even with the relatively low levels of extravehicular activity projected for the anticipated Space Shuttle Orbiter missions, NASA is reconsidering the operating pressure levels of future Orbiters and EVA equipment. Some studies have recommended that future Orbiters be operated below 620 mm Hg (12 psia), while others have stressed the development of 410 mm Hg (8 psia) EVA equipment.

Decreasing the cabin total pressure below 760 mm Hg (14.7 psia) involves various life support system design considerations. The lower atmospheric pressure will require higher ventilation flows to remove the same amount of generated heat with the lower density gas. On the other side, cabin leakage will be reduced by the lower operating pressure which should prove to be quite beneficial to a modular spacecraft considering the number of seals at each inter-

Solid Waste Management - As indicated above, the weight and volume penalties associated with food are quite high. The containment and waste from food impose one of the more significant problems in waste management. If the wastes are adequately stabilized, they may be returned to the same storage volume from where they were originally taken. However, on the long duration mission planned for the Space Station, this approach is likely to be unacceptable. A separation of food storage and waste management is likely to be imposed for health and safety reasons. Also, stabilization of microbial growth media wastes will be a necessity.

Wastes from such activities as biological experiments, medical treatment, and failed component replacement will require similar considerations to that of food waste management.

Just as on earth, waste products in space will likely be of greater volume than the original item from which they are generated. Consequently, compaction of waste products will be required on the Space Station. In the more distant future, however, chemical modification and/or recycle of many of the waste products may become desireable, but waste storage and periodic disposal will never be totally eliminated in the foreseeable future on long duration spacecraft.

EVA Frequency - Requirements and penalties associated with extravehicular activity (EVA) are reflected in various areas of life support. Not only must life support provide a pressurized mobility shelter (space garment) for the man (or woman), but it must also provide a portable life support system to support all of his basic needs while outside in space. Our current technology in portable life support systems is based entirely on the use of expendables - stored gaseous oxygen, lithium hydroxide for CO_2 control, batteries for power supply, and water for heat rejection. The use of this system for frequent EVA sorties imposes significant penalties on both the Space Station balance and resupply mission of the Shuttle Orbiter. For this reason alone, regenerable concepts should be pursued for use in future portable life support systems on a Space Station. In addition, the use of a non-regenerable heat sink would not only save 5.4 Kg (12 lbs) of water per EVA sortie from a Space Station, but it may also be required to eliminate water contamination of instruments, sensors and surfaces which are located outside the space vehicle. The use of a regenerable CO_2 control subsystem would save another 2.9 Kg (6.5 lbs) on each EVA sortie, but may require regeneration equipment and servicing provisions to be added to the Space Station life support system functions.

EVA sorties are a necessary and important element of the Space Station. The penalties for EVA use and the impact of EVA on the vehicle life support system design must be considered. With regenerable life support concepts, the penalties imposed by EVA will be somewhat reduced, but likely will never be totally eliminated.

Emergency Provisions - The influence of these requirements on the life support system was covered above under the Vehicle Configuration discussion.

SYSTEM CONSIDERATIONS

As noted earlier, the life support system will be one of the most complex systems to be incorporated in a Space Station. Its character in this application will be a true support service a "hands off" mode. This service must be able to be taken for granted by the crew in order to allow them the freedom to perform their intended mission of working in space. The crew's time is important. It has been estimated in the SOC study that it will cost between 100,000 and 200,000 dollars per man-day to perform a Space Station mission. For comparison, a 21 day, 7 man crew in a Shuttle Orbiter with a Spacelab module requires between 500,000 and 1,000,000 dollars per man-day.

The life support system must achieve a degree of automation, reliability, and endurance life that minimizes crew time and attention. It must require minimum maintenance, demand minimum crew attention during resupply, use as little as possible of the Shuttle Orbiter payload and volume capabilities, etc. These are intended to be hoarded for the primary mission objectives.

Although much technology development has been accomplished toward these life support system goals, there still remains a tremendous systems engineering and human factors task for implementation on a Space Station. The system level technology must be developed, along with the pursuit of technology options for each subsystem area. Subsystem options are required to minimize penalties on future missions where requirements have not yet firmly been established, but system level technology is the key to eventually meeting the mission goals. This section examines some of the more significant systems considerations for a Space Station.

Life Support Functions - As indicated in Table 1, nearly fifty (50) distinct life support functions are required on a Space Station. This number of functions is greater than that required for the short duration of a Space Shuttle Orbiter. Many of the life support functions provided on a short duration mission will be divided into two or more functions when regenerative technology is applied. For example, the short duration function of water storage will be replaced by four functions for long duration missions: waste water storage, water reclamation, product water quality control, and product water storage. In addition, new functions will be added for the long duration missions of the Space Station. These new functions include a solid waste compactor, refrigerator, freezer, dishwasher, a full body shower, vacuum cleaner and clothes washer. The large number of functions required for a long duration mission and their inherent functional inter-relationship makes the Space Station systems integration task very demanding.

System Integration - The integration (thermal, physical, functional, control, monitoring, etc.) of the nearly 50 diverse functions included in a life support system will be a most formidable task. Failure or degraded performance by one function cannot affect the operation or performance of other functions. The output or product of one function must be compatible with the next process, even with greatly varying loads and conditions. Subsystem concept selections must be made at the system level. History has taught us that subsystem comparisons can be greatly misleading without full consideration of the system level impact.

Maintenance - Is a common liquid thermal transport loop (which is used to thermally, functionally, and physically integrate the various life support subsystems) still a viable approach for a Space Station? Reference 4 discusses this issue in some detail. The SOC study has generally accepted the traditional liquid thermal approach. The SOC study has also specified that virtually all equipment be maintainable in order to achieve the 10 to 20 years operational lifetime. However, the penalty for this feature (which requires the installation of a large number (hundreds) of zero gravity, zero leakage, maintenance disconnects) has proven to be staggering in the past. Consequently, the author feels that this area still requires much more investigation and development activity.

Studies have shown that as we progress from Space Shuttle type technology towards regenerative life support, the number of valves required in a system could increase by as much as tenfold. In order to minimize resupply penalties, crew time and training, on-orbit spares storage and inventory control complexity, commonality of components will become a necessity. A few different valve sizes could be used with minimum penalty for all of the many different plumbing and ducting sizes anticipated.

Fault detection, isolation, and post-repair verification is an integral part of maintenance and is a major technology development area. The complexity and large quantity of interactive functions within a regenerative life support system make automation a necessity. Questions must be answered as to what level should automatic failure isolation be extended and as a corollary, to what level should failed equipment replacement be made - subsystem, major subsystem elements or component grouping, or components. Below the component level, maintenance and repair have always been considered as shop activities (within the spacecraft or returned to the ground). Progress has been made under the Shuttle program relative to automatic monitoring and check out of life support system status, off-limit detection and notification, and recommended action for correction of out-of-tolerance conditions. However, much more technology development must be accomplished to meet the true "hands off" life support system operational goal on the Space Station.

Equipment Life - Current Shuttle Orbiter technology requires that the installed equipment perform over a 10 year period intermittently for a total of 20,000 hours of operations. This is equivalent to over two years of continuous operation. The Space Station will require 10 to 20 years of continuous operation before replacement. To meet these life requirements, low stress designs must be incorporated whenever possible, easy maintenance (repair or replacement) of limited life and high stress items should be provided, and failure prone concept designs must be avoided.

Flexibility - The Space Shuttle life support system is designed to handle variable loads (crews from 4 to 10, payload heat loads from 0 to 8.5 kw, etc.). The Space Station equipment will have to manage even greater load variations and on a less controlled or planned basis. As an example, in any single habitability module, the life support system may have to go from no crew to the full spacecraft crew complement in very short periods. To avoid the penalties of installing a maximum crew complement sized life support system in every module, the specified operational parameter limits for each affected functional subsystem will be allowed to change for the relatively short duration periods of overload anticipated. Table 3 illustrates some typical overload performance parameter changes as developed on the SOC study (Reference 1).

LIFE SUPPORT SUBSYSTEMS

The selection and implementation of the most appropriate or beneficial concepts for each functional area are major considerations in the design of an efficient and practical life support system for a Space Station. Selection of subsystem concepts which are derived from basically sensitive processes, which possess inherently limited performance capability, or where the process has been improperly developed (primarily due to lack of system impact considerations), could impose significant penalties on the operation and maintenance of the life support system. Where subsystem concept alternatives exist, it is generally a major issue as to which is the correct one to select. This issue is further complicated by the prejudice of the individual or organization that conceived and/or developed each of the different subsystem concepts in contention.

Due to the large number of subsystems required in the broad functional spectrum of life support, only a few of the subsystem or functional areas (where significant system impact issues currently exist or where optional approaches are currently in contention) will be covered. Specifically, these include CO_2 Management, O_2 Supply, and Water Management.

Carbon Dioxide Management - The control, removal and post-collection processing of CO_2 effects both the system arrangement and the number of functions required. In addition, there are currently a number of viable options to select from for the various space facility applications noted in Table 2.

Table 3. Typical life support requirements for overload conditions

Parameter	Units	Normal Operation	90 Day Degraded	14 Day Emergency
Maximum crew	Per orbital work base	8	8	12
Maximum crew	Per habitability module	4	8	8
CO_2 partial pressure (maximum)	mm Hg	3.8	7.6	12
Temperature	°C (°F)	18.3 to 23.9 (65 to 75)	15.6 to 29.4 (60 to 85)	15.6 to 32.2 (60 to 90)
Dew point temperature	°C (°F)	4.4 to 15.6 (40 to 60)	1.7 to 21.1 (35 to 70)	-1.1 to 23.9 (30 to 75)
Ventilation	m/s (ft/min)	0.08 to 0.20 (15 to 40)	0.05 to 0.51 (10 to 100)	0.03 to 1.02 (5 to 200)
Wash water (minimum)	kg/man day (lb/man day)	18 (40)	9 (20)	0 (0)

For the Shuttle Tended and possibly even the early Space Station, which become operational before oxygen recovery from CO_2 becomes beneficial, three different regenerable CO_2 control concepts are currently viable. These concepts include solid amine, electrochemical, and molecular sieve based processes. Most recent studies have indicated that the solid amine concept is the most attractive and, with its technology demonstrated in previous manned tests, it is the most likely candidate for these missions. In addition, the solid amine utilizes a low grade steam desorption technique to drive absorbed CO_2 from the collector bed and, therefore, it can easily be adapted on orbit to the role of a CO_2 concentrator when the incorporation of O_2 recovery from CO_2 is desired.

Even though molecular sieves have been very successfully used on skylab, their sensitivity to long term degradation is still a concern. In addition, the penalties associated with growing molecular sieves into the CO_2 concentrator role imposes higher penalties than the other two CO_2 removal concepts for application to the Space Station.

The technology to apply electrochemical CO_2 concentrators to spacecraft is well advanced, but their sensitivity to both operating and non-operating conditions poses concern in their application to a Space Station. Both temperature and humidity significantly influence their performance and operation.

Additionally, the electrochemical process, which is similar to a fuel cell, consumes oxygen from the cabin atmosphere and requires hydrogen to operate.

On the SOC study (reference 3), the two leading concepts for the CO_2 concentrator role (solid amine and electrochemical) were compared in some detail on both a subsystem and system level. The solid amine approach was selected since it showed clear advantages in the following areas:

- Solid Amine can be implemented with less than one-half the weight of the electrochemical approach.
- Solid Amine requires less than 60% of the volume of the electrochemical subsystem.
- Solid Amine can be implemented without backup chemical CO_2 control. Electrochemical requires backup provision.
- Use of Solid Amine does not require oversizing of the electrolysis system. The electrochemical process consumes oxygen.
- Solid Amine does not require the plumbing of hydrogen lines inside the habitat. The electrochemical process requires hydrogen for its operation.
- Electrochemical has a caustic material carryover potential. Solid Amine does not contain such materials.
- Solid Amine can operate over the full cabin humidity range. Electrochemical requires additional equipment to control the process stream humidity within a narrow range.
- Solid Amine can be exposed to a vacuum environment as an alternate means of operation or during an emergency cabin depressurization. The electrochemical process would be irreversably damaged by vacuum exposure.
- Solid Amine is a cyclical process which can be designed to effectively match the cyclic generation of electrical power from solar cells. The electrochemical process favors continuous operation.
- Solid Amine is inherently less costly than the electrochemical subsystem.

There are other potentially attractive concepts (such as solid electrolyte and fused salts) which have been investigated, but their development status is inadequate to realistically consider their availability and benefits at this time. Consequently, it is projected that the Space Station, if initiated within the next 5 to 10 years, will utilize a solid amine CO_2 concentrator.

It is assumed from the results of past and current studies (including SOC), that a process to recover oxygen from the collected CO_2 will be both desireable and beneficial for the Space Station. The two prime candidates (at this writing) for this role are the Sabatier and the Bosch processes, although other processes have been and are continuing to be investigated. The Sabatier is well ahead in development status and requires less maintenance than the Bosch. Consequently, it is projected that Sabatier would be selected for the CO_2 reduction role on the pace Station.

Oxygen Supply - The long duration of a Space Station will likely require the use of water electrolysis to generate oxygen unless the scavaging concepts noted earlier are implemented. An electrolysis unit will use reclaimed water and water from the CO_2 reduction subsystem plus resupplied water as required, to maintain an overall mass balance of water within the vehicle.

A number of variations of the electrolysis process are under development, including Water Vapor Electrolysis (WVE), Solid Polymer Electrolysis (SPE), and two or three other less mature concepts. The primary differences in concepts lie in the water feed, the electrolyte type, and the electrolyte retention method. The differences in penalties, performance, and operation are generally relatively small. Selection of any particular electrolysis concept, therefore, would generally be based on development risk and desired water feed approach. However, with the high frequency EVA scenario of the Space Station, the requirement to recharge the portable EVA life support system with high pressure oxygen (up to 6,900 kPa or 1,000 psi) must also be considered. The issue then revolves around a single electrolysis unit that can operate in both low (cabin) and high (recharge) pressure modes, or two different units, one to perform each pressure level function. Operation at high pressure would eliminate the WVE concept immediately and some of the liquid feed concepts due to the excessive penalties in trying to incorporate high pressure operation. On the other hand, the use of the same unit to perform both functions is also unlikely for the required mission life (10 to 20 years) based on maintenance, wear out, and necessary redundancy considerations. Although, the SOC study (reference 3) has indicated a preference for a single electrolysis unit to perform both functions, it is more likely that two different units (and possibly even two different concepts) will be selected. The premise of this projection is based principally on the following factors:

- The life requirement of 10 to 20 years is well beyond the demonstrated technology in electrochemical devices. Consequently, maintenance will be mandatory and likely, relatively frequent over that time period. And maintenance of high pressure equipment, particularly oxygen equipment, is always a delicate procedure, fraught with potential safety hazards.
- Selection of two different units, one for each pressure level function, provides the benefits and advantages of (1) lower operating time on the high pressure mode unit and thus, less maintenance; (2) concentration of the required maintenance actions on the more continuously operating, less sensitive, low pressure mode unit; and (3) capability to use the lower operating time, high pressure mode unit as a back-up oxygen source during maintenance of the other unit and for emergency oxygen generation.

Based on the premise that two (different operating mode) electrolysis units will be selected for the Space Station, the WVE concept remains a viable candidate for the low pressure, atmosphere revitalization, oxygen supply unit. Also, WVE and SPE are both well advanced in technology development, with SPE currently having a slight lead. For the high pressure application, SPE has a distinct lead in technology development over any other existing concept; however, some of the other concepts currently under investigation (if successful) could rapidly surpass the SPE for the high pressure mode application. Predicting the best electrolysis unit for the space Station application is difficult. Based on the SOC study, the most likely concept to use is the Solid Polymer Electrolysis (SPE) for both the high pressure mode and low pressure mode applications based on its advanced development status in both areas and the economies afforded by the development of two inherently similar units.

Water Management - The benefits of reclaiming and conserving water on any significant duration (30 days or more) spacecraft have been well documented in the past and current literature. Short duration missions, such as the Space Shuttle Orbiter, consume between 4 and 5 kg/man-day of water without EVA considered. The SOC study (reference 1) indicates that long duration missions could require six (6) times that amount of water (up to 26 kg/man-day) because of the addition of clothes washers, showers, and frequent EVA sorties. On this basis, without water reclamation, the water required (over 18,000 kg or 40,000 lb) for a Space Station on every 90 day resupply visitation would be well over half of the Space Shuttle Orbiter payload launch weight capability. Consequently, the benefits of reclaiming, conserving and reusing water are obvious, yet the technology status of the required devices and support equipment are still not fully developed.

Another significant factor in the introduction and use of water recovery on a Space Station is crew acceptance of recycled water. This could take some time and considerable conditioning of the crew to implement on long duration missions.

The Space Station crew will generate over 22 kg/man-day (nearly 50 lb/man-day) of wastewater which must be processed to return it to a reuseable state, preferably to a potable quality level. Previous studies, including the initial SOC study (reference 6) had assumed that a different processing concept would be used for each wastewater type. Specifically, it was assumed that urine would be processed by a distillation concept, wash water would be processed in a hyper-filtration unit, and multi-filtration would be used to process humidity condensate and product water from the CO_2 reduction subsystem. The SOC study concluded that this approach not only adds unnecessary complexity to the life support system, but that some of the concepts may not be adequate to process the wastewater under all conditions. From this, the SOC study concluded that all wastewaters should be processed with one concept - a distillation unit which provides the most comprehensive clean up of water. The single processing concept also provides the further benefits of lower total weight (18% less installed weight and 84% less resupply weight) and volume (10% less installed volume and 89% less resupply volume). In addition, the single concept supplies inherent provisioning of back-up capability via the installation of two or more of the same units to manage the entire water processing load. The one penalty in selection of the single concept approach is slightly higher power consumption (less than 9% higher).

Currently, the NASA is pursuing the development of two candidates for application in this important Space Station life support function - a vapor compression distillation (VCD) approach and a thermoelectrically integrated, membrane evaporation system (TIMES) approach. The technology demonstrated and penalties associated with each concept is about equal and both concepts integrate into the life support system in the same way. However, the TIMES concept offers the advantages of positive separation of product water and wastewater, and the potential of longer life and higher reliability due to the absence of dynamic components in the basic process. Consequently, the TIMES concept is the most likely to be selected for the Space Station. However, both concepts should continue to be developed, along with investigation of any new ideas that may appear in the future, because of the importance and benefits of this functional area to life support.

SUMMARY AND CONCLUSIONS

Within the framework of the current Space Station studies (i.e., the Space Operations Center and the Manned Space Platform), it is possible to project a life support system from today's subsystem technology base. The SOC study (references 1, 3, and 5) defined the most likely system configuration, indicated subsystem concept selections in some of the critical areas, and recommends technology development in many of the functional areas of life support. This paper generally concurs with these positions and has made some additional projections. Table 4 highlights these positions in the key functional areas of life support. It denotes some of the areas where new technology developments are required or could provide further benefits. It also indicates some key areas where technology developed for the Space Shuttle is adaptable. The table also selects the application of specific advanced technology concepts currently under development for NASA.

Table 4. Projection of most likely life support concepts for key functional areas

Life support function	Most likley concept or technology derivative
Environmental control	
Humidity control	Space shuttle heat exchanger/condensate collector technology
Ventilation	Space shuttle fan technology (115 Vac, 400 Hz.)
Atmosphere revitalization	
Oxygen supply	Solid Polymer electrolysis (SPE)
Atmosphere diluent supply	Catalytic decomposition of hydrazine
Carbon dioxide concentration	Solid amine-steam desorbed
Carbon dioxide reduction	Sabatier
Water management	
Water reclamation	Themoelectrically integrated membrane evaporation system (TIMES)
Water quality monitor	New technology to be developed
Waste management	
Fecal collection & management	Modified space shuttle technology
Food and microbe-prone waste collection & management	New technology to be developed (could be integrated with fecal collection & management)
Food service	Space shuttle technology (at least on early space station)
Thermal control	Space shuttle pump and heat exchanger technology with improved radiators and low cost cold plates.
Health and hygiene	
Personal hygiene	New technology full body shower plus space shuttle hygiene equipment technology.
Housekeeping	New technology vacuum cleaner
Clothes cleaning	New technology clothes washer (could be chemical dry cleaning process).
Habitability, operations and safety	Space shuttle and new technology plus zero gravity furniture & work bench designs
Extravehicular activities (EVA)	
Space suit	New or improved space shuttle technology
Portable Life Support (PLSS) provisions	Modified space shuttle technology to include some regenerable functions
EVA equipment servicing & recharge	High pressure O_2 SPE plus new technology to support regenerable PLSS functions

In conclusion, the technology is currently available or is well along in development to initiate a program to put man in space for the conduct of useful tasks on relatively long duration missions. However, for a full operational capability Space Station, there are many areas of technology yet to be developed and even others yet to be conceived. Consequently, many of the current research and development activities should continue and others should be initiated to assure the availability of the required life support technology to meet the demanding requirements and expanding needs of the Space Station in the future.

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