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Method for Optimal Configuration of an ECLSS on the Space Station Freedom

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1.0 Abstract

The establishment of a permanently manned Space Station represents a substantial challenge in the design of a life support system, specifically in the need to supply a large number of crew for missions of extended duration. The Space Station will evolve by time phased modular increments delivered and supplied by the Space Shuttle and other advanced launch systems. With the addition of each subsequent phase or alteration of mission duties, the requirements of the Station may differ from previous phases of development. With the addition of future crew and pressurized volume throughout the lifetime of the Space Station, change-out of individual subsystems may be necessary in order to meet the performance, safety, and reliability levels required from the Environmental Control and Life Support System (ECLSS).

The analysis of this system growth demands the capability for advanced, integrated assessment techniques so that the unique mission drivers during each phases and mission scenario may be identified and evaluated. In order to determine the impacts of the interdependency between the ECLSS, the crew, the various user experiments, and the other distributed systems (i.e. Electrical Power System, Thermal Control System, Fluid Management System, etc.), consideration must be given to all Space Station resources and requirements during the initial and subsequent evolution phase. Therefore, it is necessary for analysis efforts to study the long term effects of established designs. These studies must quantify the optimal degree of loop closure within the capabilities of existing and future technologies including any resulting maintenance and logistics requirements. In addition, the necessity for subsystem retrofit during the lifetime of the Station must be examined. This paper will illustrate the source of system requirements due to long term exposure to the microgravity environment, review the criticality of the ECLSS functions, and describe a method to develop an optimal design during each configuration based on the cross-consumption of Station resources. (Ref. 1) A comparison utilizing this procedure will be discussed.

2.0 Introduction

With the exception of logistics, heat radiated to space, and fluids expended through leakages, venting and propulsive maneuvers, the Space Station will operate as a closed, isolated group of interacting systems. Requirements for systems and subsystems should be traceable to their source. During the lifetime of the Space

Station, many things are changing, and there will likely be experiments or operations in the future that are not well defined. Therefore, some requirements will be based on well understood needs and goals while others will be present to insure flexibility for future application. Notwithstanding, there should be a clear basis for why size, weight, power, and other design parameters have been specified and an understanding of how systems might be simplified, reduced, or changed in a favorable way based on the resources at hand during each period of the Station evolution. Analyzing this information necessitates an integrated technique which includes all of the Station fundamental design criterion. Through the modeling of the cross-consumption of Station resources determined by the supply and demand of each system, the crew, and the experiments and the basic physical parameters and constraints of the Station elements, operational trades of various alternate architectures can be assessed.

3.0 General System Description

The life support system in a manned spacecraft consists primarily of the air, water, and waste management systems.

The atmospheric control system regulates the temperature, pressure, and humidity of the spacecraft cabin atmosphere and provide necessary support for extravehicular activity (EVA) by the crew. In addition the system controls the constituents of the atmosphere, removing carbon dioxide and trace contaminants and supplying oxygen to replace that lost by leakage, metabolic consumption, and experimental use.

The water and waste management systems consist of the equipment required to provide water for drinking, cooking, and sanitation and to dispose of body wastes. In addition the water system must scrub the reused water to approved standards for human use.

Instrumentation to monitor and control the system is an integral part of the overall life support function. This instrumentation can be used to operate automatic controls or it can serve as a monitoring device with the crew interpreting the data and taking corrective actions as required.

As is shown in Figure (1), the Space Station has been functionally divided into 11 systems including the ECLSS, distributed throughout the various physical elements (i.e. the Habitation and Laboratory Modules, the Resource Nodes, etc.) (Ref. 2) There are a total of 27 functions performed by the ECLSS which have been grouped into 7 distinct subsystems. (Ref 3.) These include the Atmospheric Revitalization Subsystem (ARS), the Atmospheric Control and Supply Subsystem (ACS), the Temperature and

Humidity Control Subsystem (THC), the Fire Detection and Suppression Subsystem (FDS), the Water Recovery and Management Subsystem (WRM), the Waste Management Subsystem (WMS), and the Extravehicular Activity Support Subsystem (EVAS). Together, these life support components are responsible for maintaining a comfortable shirt sleeve environment for the crew and the internal experiments. A list of the particular functions of each of the ECLSS subsystem is shown in detail in Figure (2).

3.1 Design Parameters

In order to design an acceptable life-support system a number of design parameters must be established. Most of these are related to the physiological requirements of the crew and, therefore, are established it a large degree by the observed variations of the metabolic response during microgravity exposure. In general, the maximum, minimum, average, and in some cases the mission history of the parameters listed below must be specified for the crew members.

1. Metabolic rate
2. Sensible and latent heat rejection
3. Carbon dioxide production rate
4. Oxygen consumption rate
5. Potable and hygiene water requirements including quality standards
6. Quantities of biological and non-biological waste production
7. Atmospheric pressure, temperature, humidity, and composition

3.2 ECLSS Functional Criticality

The ECLSS is unique among Space Station systems due to the strict requirements dictated by the time criticality of several functions performed. Certain ECLSS processes must be operational on a continuous basis to maintain a minimally safe environment for the crew. For example , the loss of the carbon dioxide removal function will cause an increased concentration of CO_2 within the station, which if unchecked after a sufficient period of time, would generate a life threatening situation. Figures (3a - 3e) illustrate the survival times with the interruption of the key functions. The implication of the existence of mission critical functions is that life support technology must either include sufficient redundancy or be maintained within operational - to - critical time limits after functional interruption. In most cases, actual systems will contain a combination of both approaches.

3.3 Space Station Evolution Overview

Much of the above required data will be a function of the changing configuration of the SSF. The demand for increased space-based utilization will require accommodation for future software and hardware augmentations ("hooks" and "scars") to the Space Station (Ref. 4-6) Primary system modifications will include available electric power, thermal control, data management, internal and external laboratory facilities, and support systems and crew. (Ref. 7) In addition, fulfillment of anticipated Space Station operational support of the Space Exploration Initiative (SEI) (Ref. 8) will necessitate enhanced autonomy of all critical systems. Table (1) outlines the proposed evolution of the station and the primary characteristics during each phase of growth.

Table 1: SSF Evolution General Characteristics

Station Phase[1]	Total Power (kW)	Crew[2] (#)	Pressurized Volume (m^3)	Vehicle Servicing[3]
MTC	37.5	(4)	237	None
PMC	37.5	4	716	None
AC	75.0	8	1035	None
EOC	125.0	13	1358	OMV
LVC	175.0	16 +(4)	1392	OMV / LTV
XOC	225.0	20 +(4)	1715	OMV / LTV
MVC	225.0	20 +(4)	1715	OMV/LTV/MTV

Optimal ECLSS designs require limiting system dependency on the available support functions in order to increase the overall station operational flexibility.

[1] MTC, Man-Tended Capability, PMC, Permanently Manned Capability, AC, Assembly Complete, EOC, Enhanced Operations Capability, LVC, Lunar Vehicle Capability, XOC, Extended Operations Capability, MVC, Mars Vehicle Capability

[2] Crew numbers in parentheses represent non-permanent crew

[3] OMV, Orbital Maneuvering Vehicle, LTV, Lunar Transfer Vehicle, MTV, Mars Transfer Vehicle

4.0 General Methodology

The ECLSS can be designed utilizing many different combinations of subsystems. The optimum life-support system is heavily dependent on the mission and the design parameters enumerated above. For long duration missions, it becomes advantageous to include regeneration subsystems to reduce the weight of expendables supplied through logistic support.

The optimization procedure consists of selecting subsystems that appear best for the mission then incorporating these systems into a complete system. Further optimization studies are then accomplished to determine if this combination gives the truly optimum system. There is no assurance that a combination of optimum subsystems will produce the optimum system. Therefore, the design must follow an iterative procedure until a superior combination is established. This can be accomplished though modeling the particular characteristics of the resources provided and consumed by the various life support subassemblies.

Cross-consumption refers to the resources consumed by an SSF subsystem to produce its output resource. For example, the resource "oxygen" is produced by the Oxygen Generation Subassembly in the ECLSS and consumed by station users and other SSF systems such as the crew, module leakage, the airlock, etc. The cross consumption of station resources can be related by the equation:

$$X_i = \sum_{j=1}^{N} A_{ij}(X) \qquad \text{for } i = 1, \ldots N \tag{1.0}$$

where:

- N = Number of resources
- X = Vector of gross supplies of resources
- X_i = Gross supplies of resource i
- A_{ij} = Amount of resource i consumed to provide amount X_j of resource j

In general, each X_i will consist of a constant and a transient term representing fixed hardware and resources and periodic resupply

$$X_i = X_{oi} + dX_i \tag{2.0}$$

This study will only be concerned with the subset of the vector X, X_e. Those resources directly or indirectly required by the ECLSS.

Those resources not represented in terms of mass are then related to an associated mass penalty by the equation:

$$M = \left(\frac{M_i}{X_{oi}} + \frac{dM_i}{dX_i} \right) X_{ie} \qquad 3.0$$

where:

M = Mass penalty

M_i = Total mass associated to resource

X_{oi} = Total fixed resource production of resource i

dM_i = Δ mass to produce addition unit of resource i

dX_i = Δ resource i

X_{ie} = Amount of resource i required due to the ECLSS

For example, the resource "power", is represented in the units kW-hr/hr. The associated mass with this system includes the mass of the solar arrays, the solar alpha rotary joint, the integrated equipment assembly, and the rest of the EPS system. Therefore, each kW of power required by the ECLSS requires a power generation and storage assembly of some mass.

For reference, the masses of various architectural options can be compared with STS lift capability through the relationship:

$$N_{STS} = \frac{M_o}{M_{pl}} (pf_o) + \frac{dM}{M_{pl}} (pf_d)\, t \qquad 4.0$$

where:

N_{STS} = Number of shuttle flights

M_o = Fixed mass to orbit

dM = Logistics mass to orbit

M_{pl} = Shuttle payload mass capability

pf_o = Packaging factor, fixed mass

pf_d = Packaging factor, logistics mass

t = Orbit time

By comparing this number with shuttle manifest capability over some time period, a schedule for the optimum technology option implementation can be generated. Assumed in these relationships is the idea that subassembly efficiency is maintained constant through what ever means necessary, including additional logistics.

Using the maximum STS capability and the STS payload allocation for the ECLSS, alternate architectures can be compared using the following guidelines:

$$N_{max} = N_{STS\,max} - N_{critical} \qquad 5.0$$

$$N_{allocation} = N_{STS\,max} - N_{critical} - N_{noncritical} \qquad 6.0$$

$$\text{If } N_{STS} \leq N_{allocation} \rightarrow N_{STS} = N_{STS} \qquad 7.0$$

$$\text{If } N_{max} \leq N_{STS} < N_{allocation} \rightarrow N_{STS} = 2N_{STS} - N_{allocation} \qquad 8.0$$

$$\text{If } N_{STS} > N_{max} \rightarrow N_{STS} = \infty \qquad 9.0$$

where:

N_{STSmax} = Lift capability of Shuttle over some time period

$N_{critical}$ = STS payload allocation for critical non-ECLSS equipment/resources

N_{max} = Maximum STS payload accommodation for ECLSS

$N_{noncritical}$ =STS payload allocation for noncritical equipment/resources

$N_{allocation}$ = STS payload allocation for ECLSS

Any mass-to-orbit required beyond that allocated necessitates the removal of an equal portion of mass allocated for other systems and experiments. Thus the additional penalty used in Equation 8.0. Any SSF architecture that requires more mass-to-orbit beyond STS lift capabilities is unachievable, therefore the relationship in Equation 9.0.

5.0 Sample Comparison

The selection of the ECLSS equipment must be based upon a knowledge of the ECLSS equipment. In addition, operating characteristics of the various technologies may be dependent on the processing rates. Figure (4) shows the typical resource boundaries of the ECLSS system. Table (2) outlines three proposed ECLSS systems that could be utilized by the SSF. Each of the assemblies are identical with the exception of two subsystems. The first system utilizes Lithium Hydroxide canisters for CO_2 removal while the second system utilizes the Electrochemical Depolarized Cell and the Sabatier Carbonation Reactor for CO_2 removal and reduction, respectively. The third system utilizes the 4 Bed Molecular Sieve and the Bosch Carbonation Reactor. The ensuing Δmasses of the three systems on the SSF are broken down by resource requirement in Table (3) This information is summarized graphically in Figure (5). It can be seen that the choice of technology is highly dependent on the length of the mission, particularly when comparing regenerative and non-regenerative systems In addition, if for other reasons such as technology readiness or safety limitation a particular technology may not be implemented initially, this procedure has the flexibility to analyze the change-out of one subassembly with another during some time period by comparing the annual logistics launch load for the baseline system with that of integrating a new candidate and its required logistic support to determine if change-out would be beneficial. Table 4 lists some of the possible alternatives for the various subsystems.

6.0 Summary

A method of analysis for recommending candidate technology integration into the Space Station Freedom Environmental Control and Life Support System has been described. The applications of this procedure include resource balancing, technology change-out optimization, and ECLSS logistics requirements. Assessment of systems requires the knowledge of several mission parameters, including desired Station configuration, mission utilization scenarios, mission duration, crew size, and logistics support.

7.0 References

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Figure 1 Space Station Element & System Boundaries

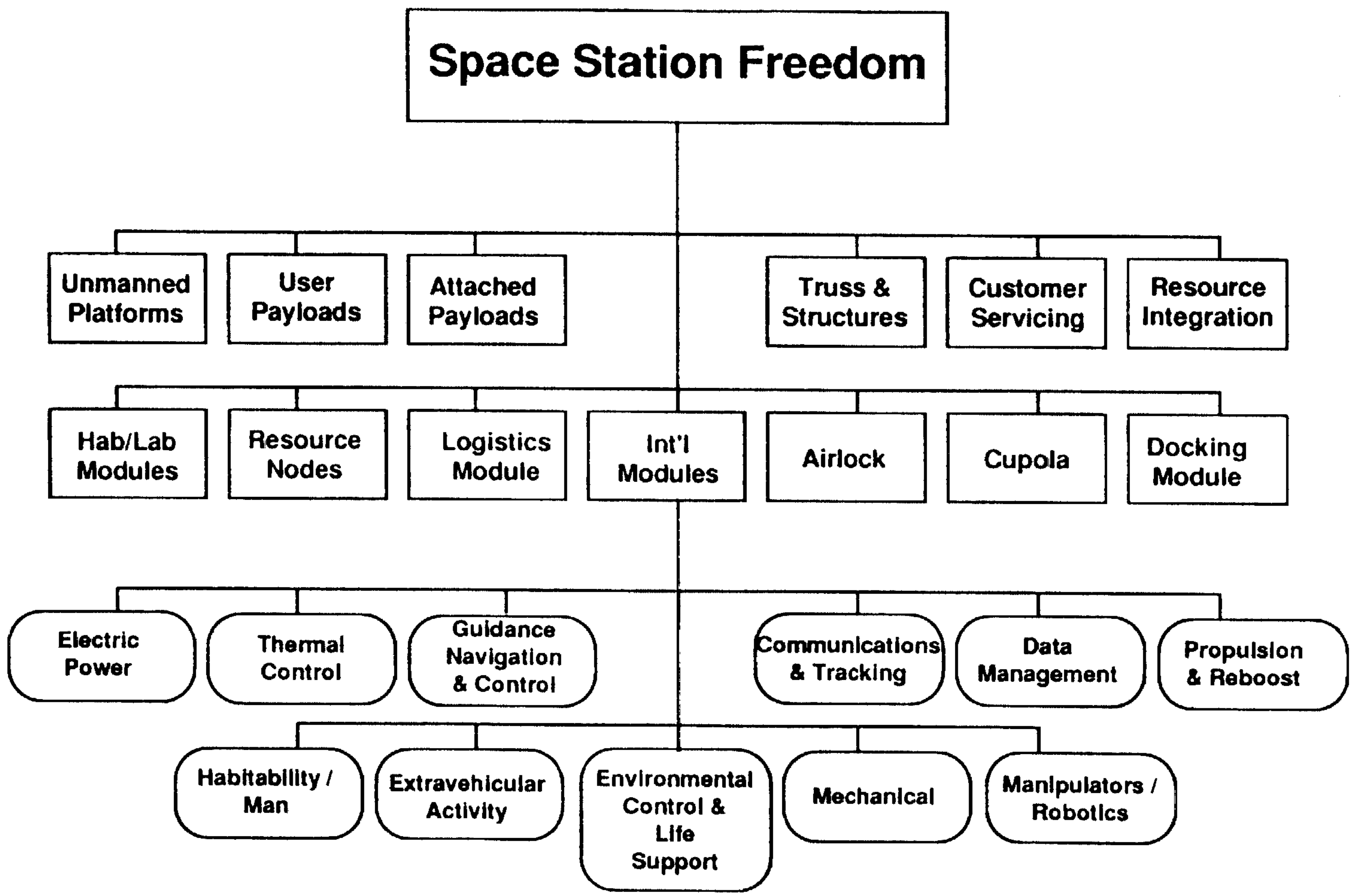


Figure 2 ECLSS Functional Divisions

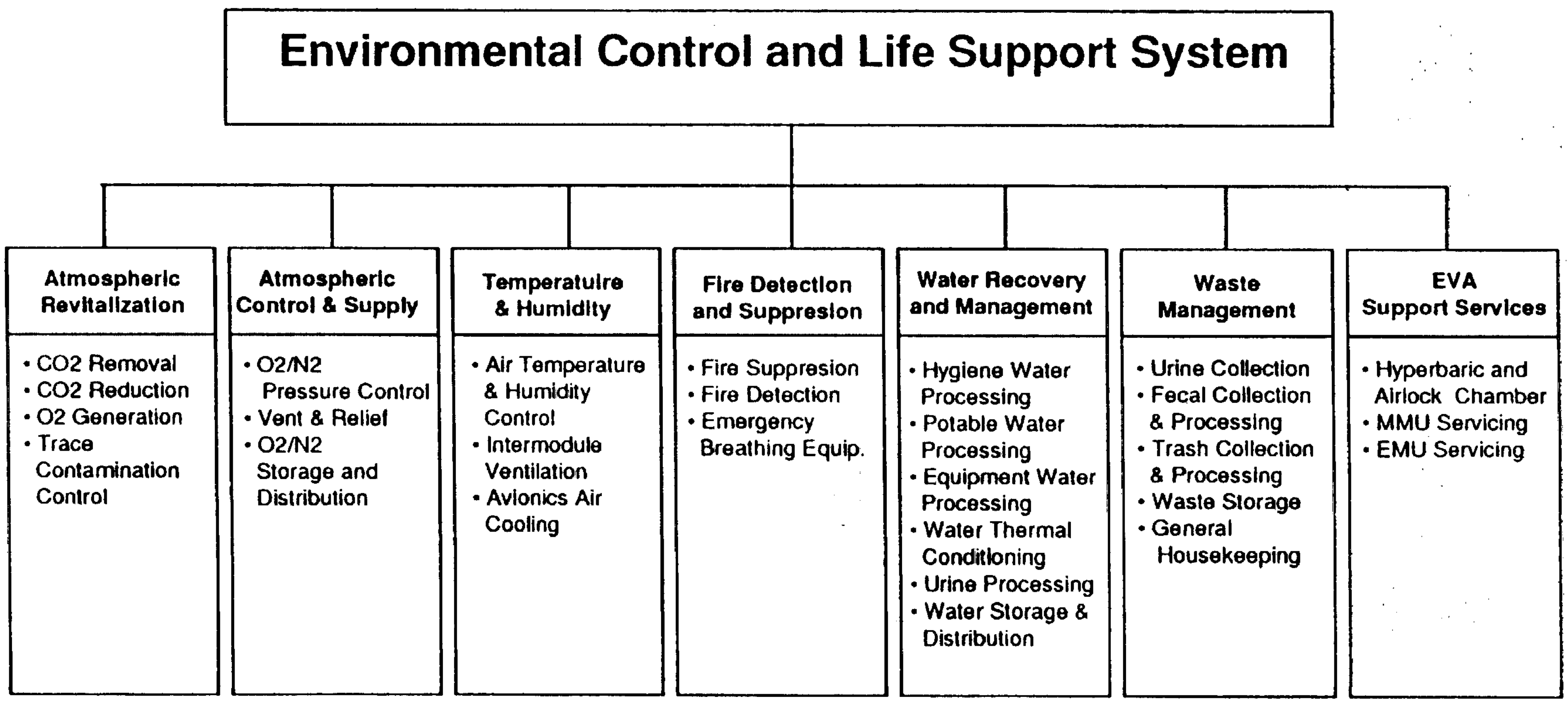


Figure 3.a
Carbon Dioxide Removal Criticality

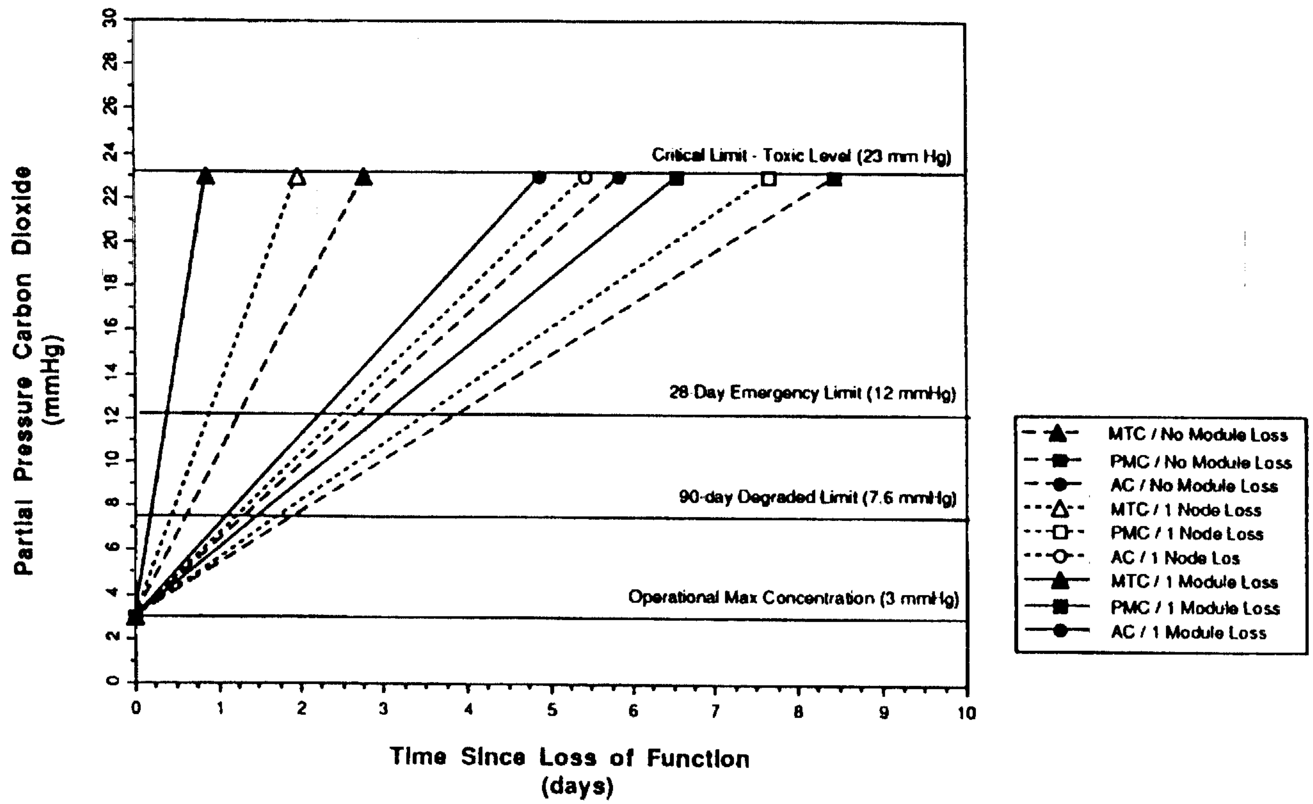


Figure 3.b
Humidity Control Criticality

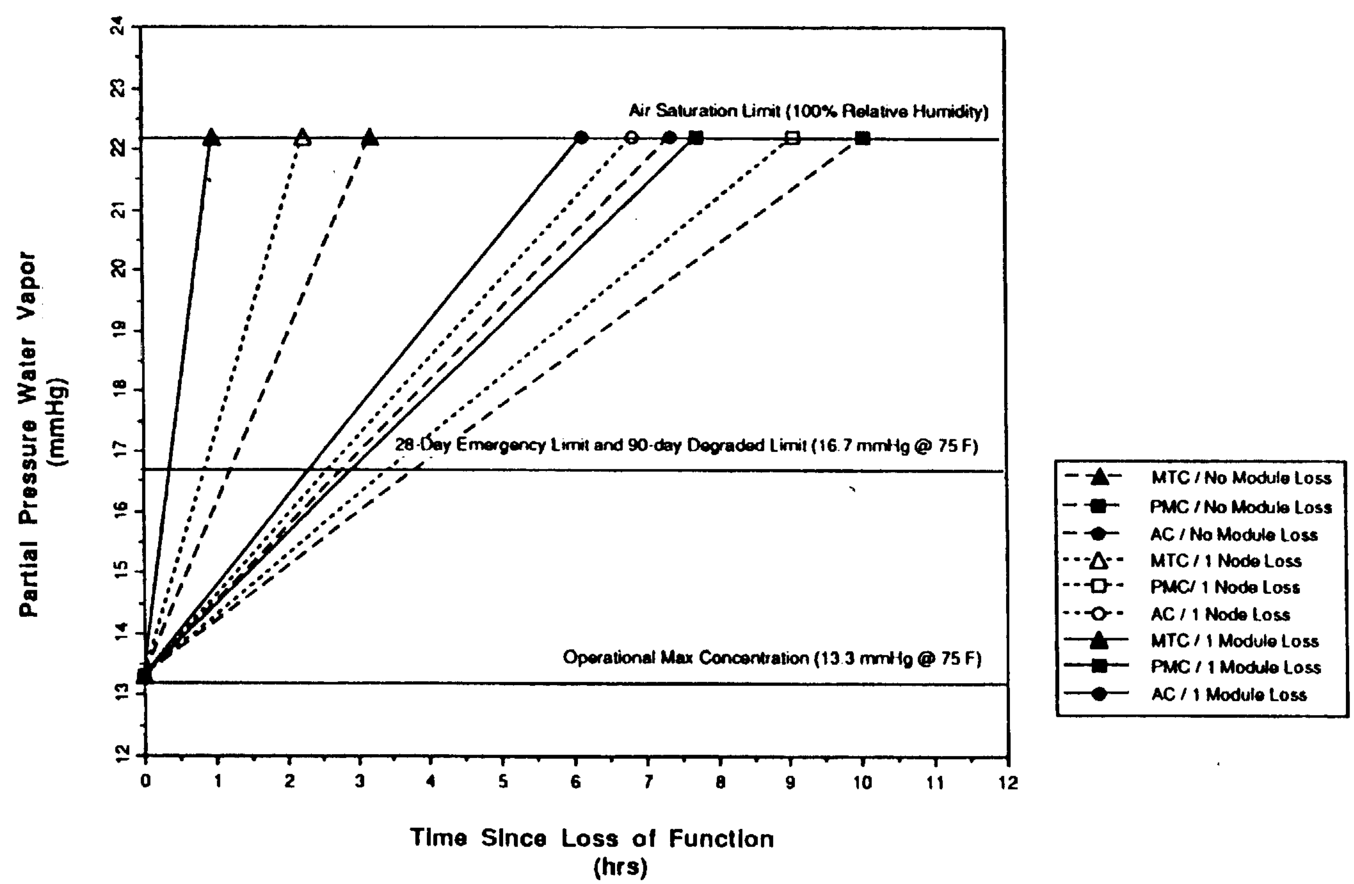
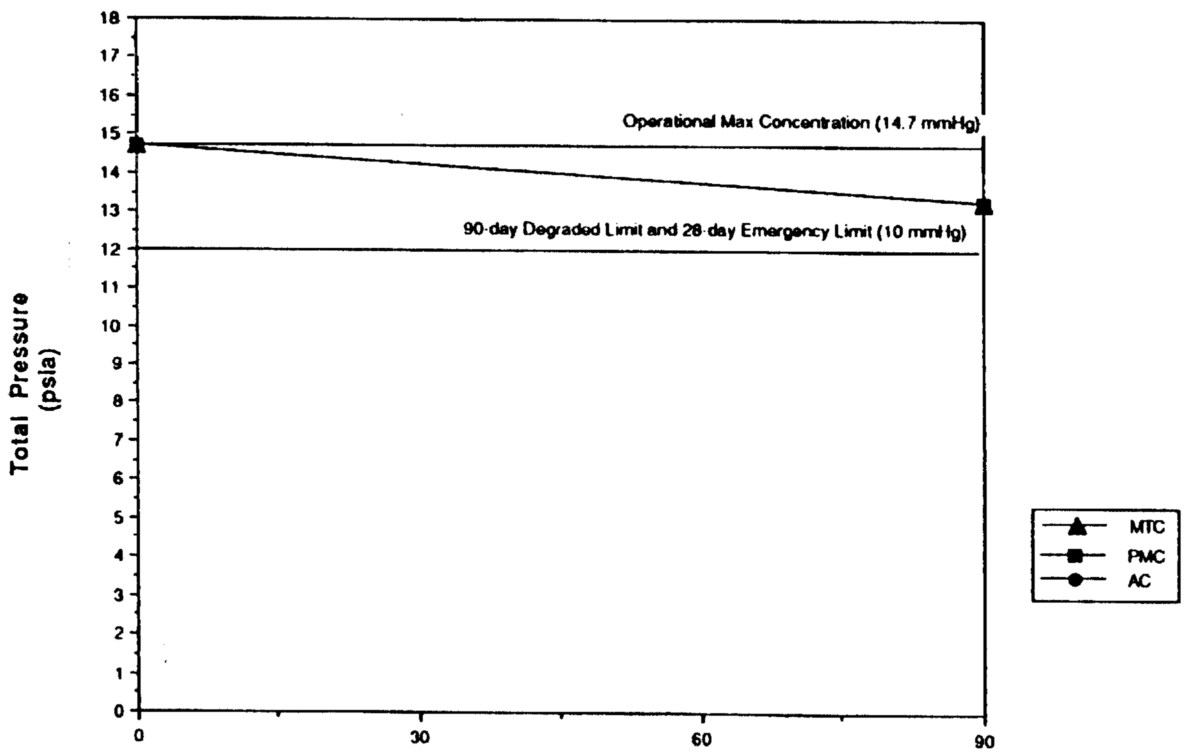


Figure 3.c
Total Pressure Control w/o N2 Supply Criticality



Time Since Loss of N2 Supply Function (days)

* Maintaining Oxygen Concentration

Figure 3.d
Oxygen Partial Pressure Supply Criticality

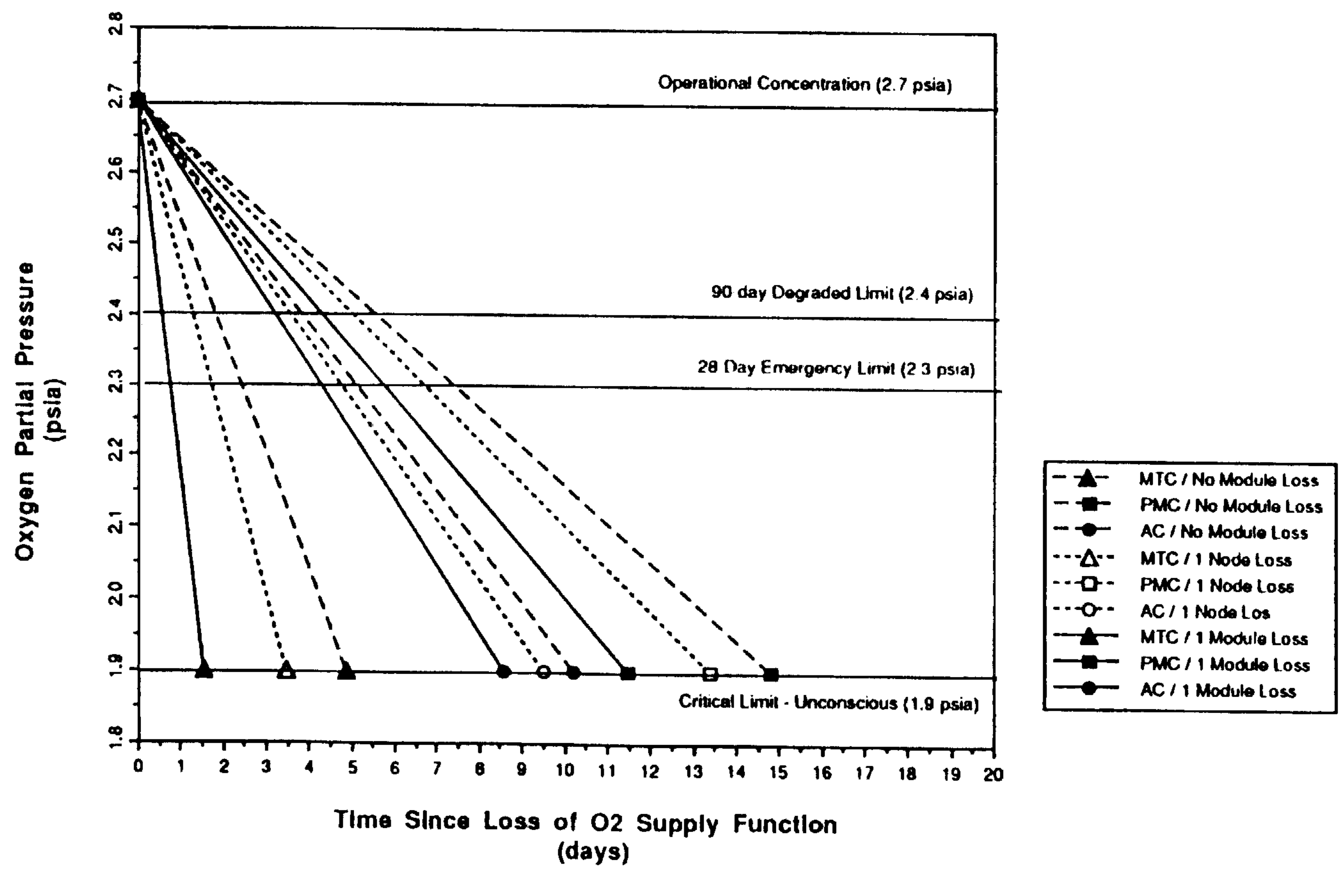
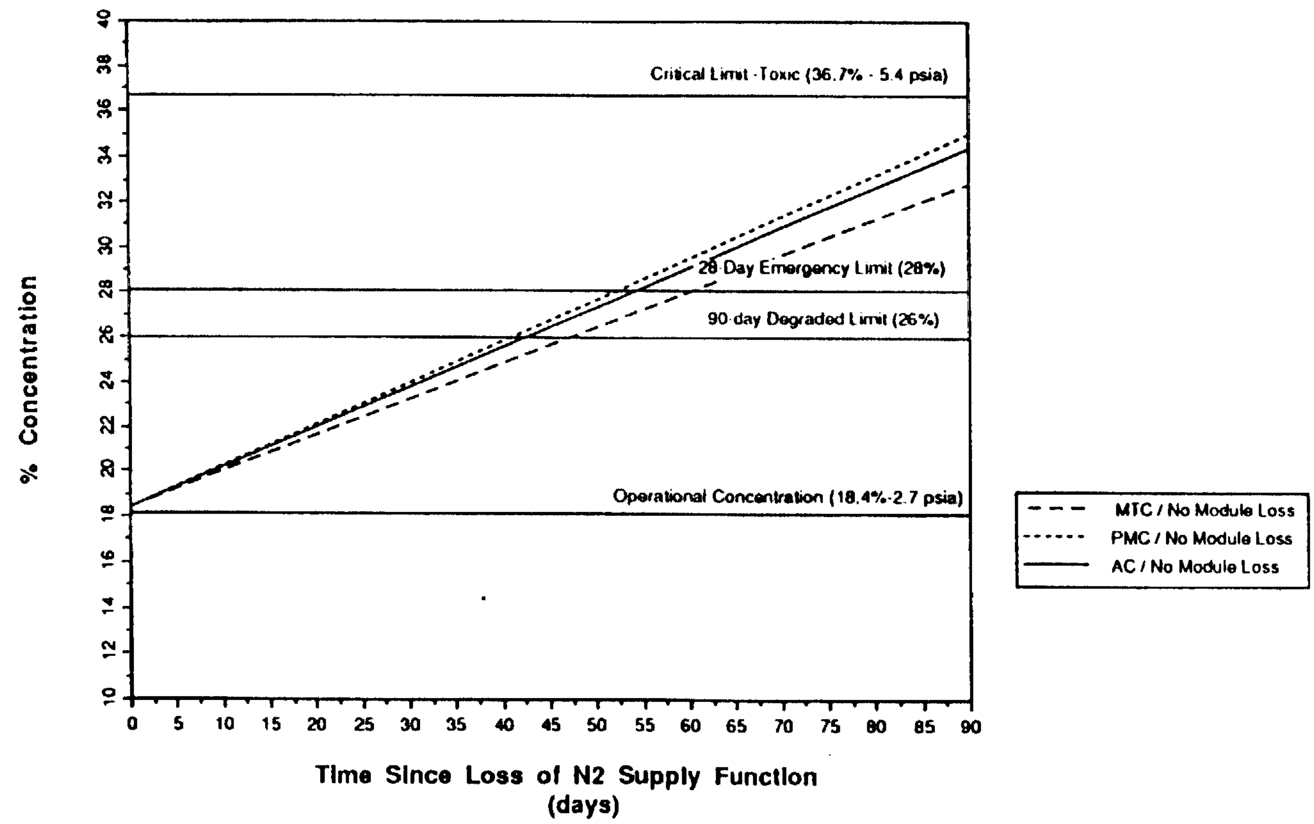


Figure 3.e
Oxygen As Total Pressure Control Criticality



* Maintaining 14.7 psia Total Pressure

Figure 4 ECLSS Typical Resource Interface Schematic

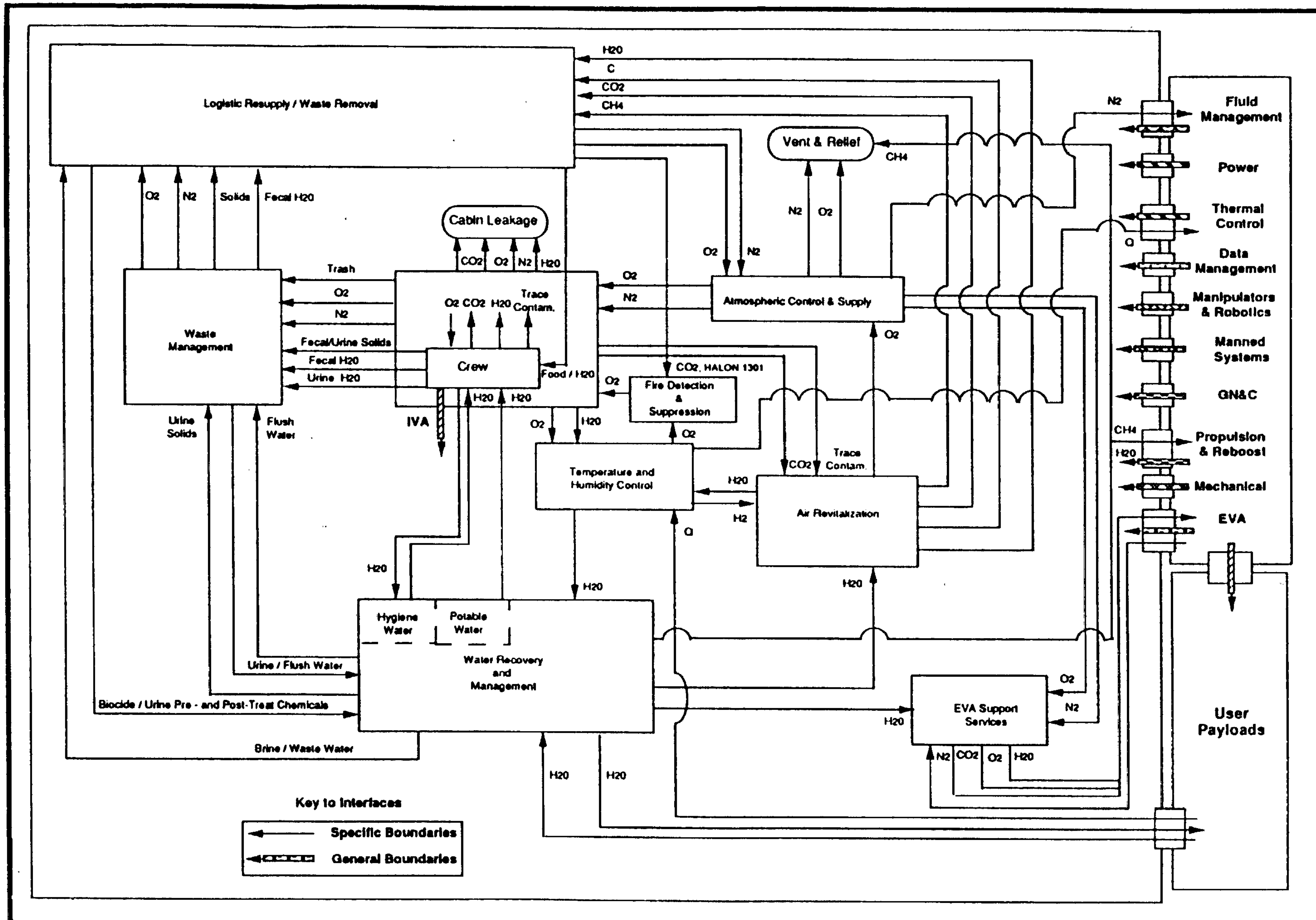


Figure 5 Sample Technologies Comparison

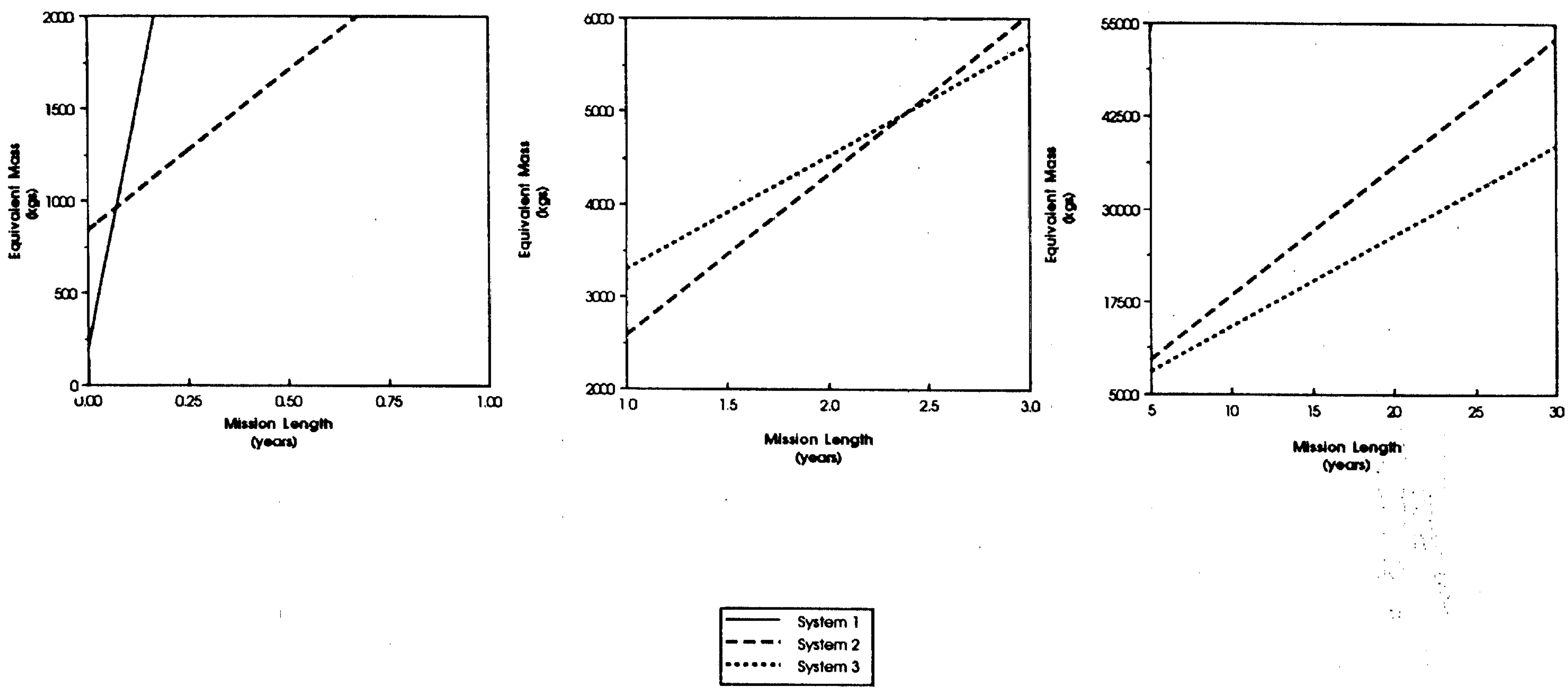


Table 2
Sample Alternative ECLSS Architectures

	System 1	System 2	System 3
Atmospheric Revitalization			
CO2 Removal	**Lithium Hydroxide**	**Electrochemical Depolarized Cell**	**4 Bed Mole Sieve**
CO2 Reduction	**None**	**Sabatier**	**Bosch**
O2 Generation	Static Feed Electrolysis	Static Feed Electrolysis	Static Feed Electrolysis
Trace Contaminant Control	Sorbents, Filters, Catalyisis	Sorbents, Filters, Catalyisis	Sorbents, Filters, Catalyisis
Atmospheric Control and Supply			
O2/N2 Pressure Control	Advanced Shuttle Technology	Advanced Shuttle Technology	Advanced Shuttle Technology
Vent and Relief	Advanced Shuttle Technology	Advanced Shuttle Technology	Advanced Shuttle Technology
O2/N2 Storage and Distribution	Cryogenic Storage	Cryogenic Storage	Cryogenic Storage
Temperature and Humidity Control			
THC	Condensing Heat Exchanger	Condensing Heat Exchanger	Condensing Heat Exchanger
Intermodule Ventilation	Advanced Ducting/Fans	Advanced Ducting/Fans	Advanced Ducting/Fans
Avionics Air Cooling	Advanced Shuttle Technology	Advanced Shuttle Technology	Advanced Shuttle Technology
Fire Detection and Suppression			
Fire Detection	Advanced Shuttle Technology	Advanced Shuttle Technology	Advanced Shuttle Technology
Fire Supression	Carbon Dioxide	Carbon Dioxide	Carbon Dioxide
Emergency Breathing Packs	Advanced Shuttle Technology	Advanced Shuttle Technology	Advanced Shuttle Technology
Water Recovery and Management			
Hygiene Water Processing	Multifiltration	Multifiltration	Multifiltration
Potable Water Processing	Multifiltration	Multifiltration	Multifiltration
Equipment Water Processing	Multifiltration	Multifiltration	Multifiltration
Water Thermal Conditioning	Advanced Shuttle Technology	Advanced Shuttle Technology	Advanced Shuttle Technology
Urine Processing	Vapor Compression Distillation	Vapor Compression Distillation	Vapor Compression Distillation
Water Storage and Distribution	Advanced Shuttle Technology	Advanced Shuttle Technology	Advanced Shuttle Technology
Waste Management			
Urine Collection	Advanced Shuttle Technology	Advanced Shuttle Technology	Advanced Shuttle Technology
Fecal Collection and Processing	Compaction/Storage	Compaction/Storage	Compaction/Storage
Trash Collection and Processing	Compaction/Storage	Compaction/Storage	Compaction/Storage
Waste Storage	Compaction/Storage	Compaction/Storage	Compaction/Storage
General Housekeeping	Advanced Shuttle Technology	Advanced Shuttle Technology	Advanced Shuttle Technology
Extravehicula r Activity Support			
Hyperbaric/Airlock Chamber	SSF Baseline Technology	SSF Baseline Technology	SSF Baseline Technology
MMU Servicing	Nonregenerative Technogies	Nonregenerative Technogies	Nonregenerative Technogies
EMU Servicing	Nonregenerative Technogies	Nonregenerative Technogies	Nonregenerative Technogies

Table3

ΔResource Comparison

	System 1	System 2	System 3
Hardware	18.1 kgs	130.6 kgs	567.9 kgs
Power	10.9 kgs	89.2 kgs	895.7 kgs
Heat Rejection	37.5 kgs	216.5 kgs	600.6 kgs
Humidity Control	92.5 kgs	92.5 kgs	0.0 kgs
Water Processing	23.0 kgs	23.0 kgs	0.0 kgs
Oxygen Generation	0.0 kgs	280.6 kgs	0.0 kgs
Spares (per year)	8984.5 kgs	1043.0 kgs	132.4 kgs
Expendables (per year)	18.2 kgs	83.2 kgs	206.4 kgs
Maintenance (per year)	1415.0 kgs	605.5 kgs	877.6 kgs
Total	182 kgs +10418 kgs.year	832 kgs +1732/year	2064kgs +1216kgs/year

Table 4 Life Support Candidate Technologies

Carbon Dioxide Removal	Carbon Dioxide Reduction	Oxygen Generation	Trace Contam. Control	Oxygen Make Up	Nitrogen Make Up
• Electrochemical Depolarized Cell • Solid Amine Water Desorbed • 4 Bed Zeolite Molecular Sieve • 2 Bed Carbon Molecular Sieve • Lithium Hydroxide • Air Polarized Concentrator	• Bosch Reactor • Sabatier Reactor • Sabatier Reactor w/ CH4 Reduction • Catalytic Decomposition • Photocatalysis • Carbon Dioxide Electrolysis • Ultraviolet Photolysis	• Static Feed Electrolysis • Water Vapor Electrolysis • Carbon Dioxide Electroysis • Cryogenic Storage • High Pressure Storage	• Sorbents • Catalytic Oxidation • Vacuum Exposure • 2 Bed Carbon Molecular Sieve • Reactive Bed Plasma	• Cryogenic Storage • High Pressure Storage • Superoxides • Hydrogen Peroxide • Nitric Oxide • Hydrazine/ Nitrogen Tetraoxide	• Cryogenic Storage • High Pressure Storage • Electroytic Urine Decomposistion • Nitric Oxide • Hydrazine/ Nitrogen Tetraoxide
Water Processing	**Urine Processing**	**Waste Processing**	**Temperature Control**	**Humidity Control**	**Fire Suppression**
• Reverse Osmosis • Multifiltration -carbon -ion exchange • Ultrafiltration • Supercritical Water Oxidation • Radioisotope for Thermal Energy • Oxidation - heat - catalysis - biological	• Thermoelectric Integrated Membrane Evaporative System • Vapor Compression Distillation • Urine Electrolysis • Air Evaporation • Flash Evaporation • Vacuum Distillation/ Pryolysis	• Compaction/Storage • Incineration • Wet Oxidation • Radioisotope for Thermal Energy • Supercritical Water Oxidation • Biodegradation • Photocatalytic Oxidation • Irradation	• Heat Exchangers • Phase change Process • Electric/Resistive Heating • Solar Heating • Utilization of Waste Heat	• Condensing Heat Exchangers • Dessicant • 4 Bed Zeolite Molecular Sieve • 2 Bed Carbon Molecular Sieve • Membrane Separtion	• Carbon Dioxide • Halon 1301

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16. Abstract

The establishment of a permanently manned Space Station represents a substantial challenge in the design of a life support system, specifically in the need to supply a large number of crew for missions of extended duration. The Space Station will evolve by time phased modular increments delivered and supplied by the Space Shuttle and other advanced launch systems. With the addition of each subsequent phase or alteration of mission duties, the requirements of the Station may differ from previous phases of development. With the addition of future crew and pressurized volume throughout the lifetime of the Space Station, change-out of individual subsystems may be necessary in order to meet the performance, safety, and reliability levels required from the Environmental Control and Life Support System (ECLSS).

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