Internal Atmospheric Pressure and Composition for Planet Surface Habitats and Extravehicular Mobility Units

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Preface

This document was produced for the NASA Johnson Space Center Planet Surface Systems Office by the Human and Habitation Systems team and the Extravehicular Activity Systems team. Inputs were made by team members and other NASA personnel who have expertise in the areas discussed in the report.

1.0 Background and Summary

1.1 Background

Proper design of the atmospheres within habitats and Extravehicular Mobility Units (EMU) is key to the development of a long-term planetary surface human outpost. Early decisions about atmospheric pressure and composition will have continuing effects, throughout the life of the planet surface program, on the outpost's habitable elements and on the activities accomplished within those elements.

For reference, the Earth sea-level atmosphere is described in Table 1.1-1. Potential space habitat and EMU atmospheric pressures range from the Earth sea-level value of 101.4 kPa (14.7 psia) to as low as approximately 25.5 kPa (3.7 psia), and potential oxygen concentrations range from approximately 20 percent up to 100 percent. Potential atmospheric diluents include nitrogen and other low atomic weight elemental inert gases.

Previous design of EMU's has shown that, with current and foreseeable technology, their internal atmospheric pressures must be lower than Earth sea-level pressure to allow the crewmember sufficient mobility and dexterity to perform useful work. The limited duration of Extravehicular Activity (EVA) excursions combined with a low suit pressure can in some cases allow a 100 percent oxygen atmosphere in the EMU without toxic effects on the EVA crewmember.

Long crew stays in a pressurized habitat, as envisioned in the Planet Surface Systems program, demand a mixed atmosphere of oxygen and diluent gas, more like that which humans normally experience on Earth, to preclude the toxic effects of a high oxygen pressure atmosphere and to control flammability hazards. This influences the habitat atmosphere design toward increased total pressure with a decreased oxygen concentration.

Many other considerations exist which may favor either increased or decreased habitat pressure and oxygen concentration within the constraints of human health and safety, but in general it is anticipated that the habitat may have a higher atmospheric pressure and a different atmospheric composition from that of the EMU.

A unique resource available to the planet surface program is the extension of the human's service and performance capabilities on planetary surfaces. This capability is provided through EVA, which involves crewmembers donning EMU's and performing operations outside the pressurized environments of habitats, shelters, or rover vehicles.

The reduction in atmospheric pressure experienced by crewmembers when moving from the habitat to perform EVA, combined with the presence of a diluent gas dissolved in their body tissues, produces the risk of decompression sickness. It is therefore necessary to relate habitat pressure to EMU pressure during the design of an integrated human habitation system. The ratio of the pressure of a habitat atmosphere diluent gas in a crewmember's body tissues to the EMU atmosphere's total pressure is designated R. The higher this value is above 1.0, the greater the statistical likelihood of decompression sickness.

The ability of the surface crew to move safely and efficiently between the habitat and the EMU is important for crew safety, productivity, and mission success. It is also important that the crew have efficient access to all elements of the habitat where they must operate. Planet surface habitats may include such diverse elements as crew quarters, laboratories, crop growth chambers, airlocks, maintenance shops, command and control centers, logistics carriers, and pressurized rovers. Just as the nature of the EMU results in constraints on its internal atmosphere, the varied nature of these habitat elements may result in different requirements on their internal atmospheres.

Table 1.1-1 Standard Sea-Level Atmosphere

Parameter	**kPa**	**psia**
Total pressure	101.36	14.70
Oxygen partial pressure	21.37	3.04
Nitrogen partial pressure	78.60	11.44
Water vapor partial pressure	1.38	0.2
Carbon dioxide partial pressure	0.04	0.0058

Note: Water vapor partial pressure at 23 degrees C (74 degrees F) and 50 percent relative humidity.

Reference 1

1.2 Historical Practice

In previous space programs, habitat pressures have ranged from 101.4 kPa (14.7 psia) to 34.5 kPa (5.0 psia), and EMU pressures have ranged from 40.0 kPa (5.8 psia) to 26.2 kPa (3.8 psia). Prototype EVA suits of 57.2 kPa (8.3 psia) internal pressure have been built and ground-tested by NASA.

For short missions, of two weeks or less, 100 percent oxygen vehicle atmospheres have been used up to 34.5 kPa (5.0 psia) and mixed oxygen-nitrogen atmospheres with an oxygen pressure equivalent to Earth sea-level have been used.

The long-term missions, including Skylab, Salyut, and Mir, have all utilized mixed oxygen-nitrogen atmospheres.

EMU's to date have all utilized 100 percent oxygen atmospheres.

Operational values for the decompression ratio, R, have historically ranged from less than 1.0 to 1.84. Some programs, such as the Space Shuttle, have used temporary reductions of habitat pressure and prebreathing of 100 percent oxygen by the EVA crew prior to decompression. These procedures lower the level of nitrogen in the body tissues, reducing the EVA crewmembers' R values at the time of decompression to the EMU operating pressure.

Adjustments to habitat pressure and prebreathing of 100 percent oxygen consume crewmember time, with an effect on Intravehicular Activity (IVA) crew productivity. It has therefore appeared desirable to minimize or eliminate these operational requirements in programs such as Space Station Freedom, where EVA may be frequent.

The current Shuttle EMU operates at 29.6 kPa (4.3 psia) for maximum mobility. The potential physiological effects of a decompression from the 101.4 kPa (14.7 psia) Shuttle cabin to the operational suit pressure level require oxygen prebreathing by the EVA crewmember. In order to eliminate nitrogen gas from their bodies, EVA crewmembers breathe 100 percent oxygen during a "washout" period. The protection against decompression sickness offered by this nitrogen washout is a function of the duration of prebreathing prior to exposure to the oxygen in the starting and reduced pressure atmospheres. On Shuttle, prebreathe operations can be performed in basically two ways: 1) have the EVA crewmember breathe 100 percent oxygen for 4 hours prior to conducting an EVA operation, although this procedure imposes additional time constraints and hardware requirements on the crewmember as well as on mission operations, or 2) prebreathe oxygen for 60 minutes at 101.4 kPa (14.7 psia), then decrease total cabin pressure to 70.3 kPa (10.2 psia) for 24 hours prior to an EVA operation followed by 40 minutes of prebreathing which is accomplished while in the EMU prior to conducting an EVA. The latter of the two operational modes is currently used for Shuttle. In staged decompressions involving multiple pressure reductions, the R value should be maintained below 1.0 until the last decompression.

For Space Station Freedom orbital operations in support of routine activities, it was recognized that EVA preparation "overhead" needed to be reduced or eliminated to fully utilize EVA as a viable capability. Elimination of prebreathe operations would enhance on-orbit crew productivity, make EVA operations more routine in nature, and make multi-EVA missions easier. One approach to elimination of prebreathing timelines, procedures, and ancillary supporting hardware was to develop a high operating pressure (57.2 kPa/8.3 psia) space suit. Although this higher pressure suit technology was successfully developed and demonstrated in support of the Space Station advanced technology baseline, the structural elements of the major suit components were necessarily heavy and the higher operating pressure impacted the acceptable limits of hand-glove performance.

1.3 Study Summary

The study described in this report has investigated a wide range of considerations and constraints on the integrated design of habitat and EMU atmospheres. It was performed by the Human & Habitation Systems team and the EVA Systems team, both centered at the NASA Johnson Space Center, based on a request from the Manager, Planet Surface Systems Office. Inputs were gathered from reference materials, from team members, and from other NASA personnel with expertise in the effects of atmospheric pressure and composition on humans and systems. The body of this report, sections 2.0 through 6.0, describes the investigated parameters.

The impacts of habitat atmosphere pressure and composition were classified as to their effects on research and technology development (the need for new data), design (system mass/volume/power), and operations (crew productivity/logistics resupply).

Results from the study, which are discussed in sections 7.0 and 8.0, include:

- integrated considerations and constraints,
- potential design strategies for planet surface habitat / EMU atmospheres,
- the need for further program-level decisions and guidance,
- needs for research and technology development to support the future selection of an optimum strategy and internal atmosphere point design,
- conclusions and recommendations which are based on particular program goals, mission architectures, and systems designs.

2.0 Human Physiology Considerations and Constraints

The following subsections describe attributes of human physiology and human performance which may influence the design of the habitat and EMU atmospheres.

2.1 Total Pressure

The human body requires an atmospheric pressure to maintain normal physiologic processes. Below 6.3 kPa (0.9 psia) water will vaporize at body temperature.

Changes in total pressure can be tolerated by regulating the rate of pressure change. Reduction of total pressure beyond a point is accompanied by evolution of dissolved gases in body tissues. The parameter used to measure the likelihood of diluent gas evolution is R, the ratio of the sum of the initial pressures of all dissolved diluent gases to final total atmospheric pressure. When R exceeds 1.0, gases dissolved in body tissues may be evolved as bubbles. Bubbles in the venous circulatory system are commonly known as venous gas emboli (VGE). Symptoms produced by gas bubble evolution range from a tingling or burning sensation on the skin to joint pain to death, depending on the severity of the decompression and the length of time involved. The general term associated with these symptoms is known as decompression sickness (DCS). Incapacitating symptoms are designated grade 3 decompression sickness. Figure 2.1-1 shows the results of testing which illustrate the increased risk with increasing R value of a) venous gas bubbles without symptoms, b) all symptoms of decompression sickness including very mild symptoms, and c) symptoms that impair performance and are likely to result in early termination of an EVA (reference 2).

An R value of more than 1.0 may have a risk of decompression sickness. This risk increases with increased R value. The risk of decompression sickness during a mission is statistically cumulative over a number of decompressions during that mission; therefore, the mission duration and frequency of EVA must be considered when determining an appropriate value for R for a given mission. A statistical analysis of cumulative risk shows that for R=1.22, the risk of decompression sickness after ten decompressions is 7 percent, while for R=1.4 the risk is 37 percent. Therefore, cumulative risk is an important criterion for long-term planet surface missions and it increases rapidly as R is increased above 1.0. If the decompressions are not separated by enough time to eliminate previously formed gas bubble nuclei from body tissues, the risk of decompression sickness on subsequent decompressions is also greatly increased.

Atmospheric pressures and gas mixtures other than Earth sea-level may produce several other effects on the human. Heart rate, electroencephalogram, mineral loss, and blood constituents may be affected. Changes in factors such as body moisture loss, comfort, and fatigue may be induced by reduced atmospheric pressure. Unknown effects may exist for the immunologic/endocrine system (reference 3).

2.2 Oxygen Pressure

The human requires oxygen pressure in the lungs to maintain normal respiration and blood oxygenation. Figure 2.2-1 illustrates the relationship of oxygen concentration to atmospheric pressure which is defined as the normal sea-level equivalent for humans. When atmosphere pressure is reduced, the critical level of oxygen for the human to assure adequate oxygenation is not the oxygen concentration or the partial pressure of oxygen. It is the alveolar oxygen, the partial pressure of oxygen available in the alveoli (small air sacs) of the lungs for oxygen transport. The Earth normal level of alveolar oxygen is 13.7 kPa (2.0 psia).

Figure 2.2-2 (reference 1) shows the effects of increased or decreased oxygen concentration on the human as a function of total atmospheric pressure. The condition of insufficient oxygen pressure is termed hypoxia and results in symptoms as severe as death, dependent on the degree of oxygen lack and the exposure time. The human can acclimatize over time to oxygen levels somewhat lower than the normal range, but the parameters of time and pressure are not clearly known. A common example of acclimatization is the case of humans who live in high altitude locations on the Earth. Total pressure at altitude is decreased and oxygen concentration is constant, resulting in a lower oxygen pressure.

Excess oxygen pressure, above that which the body normally experiences, produces symptoms of the condition known as pulmonary and central nervous system oxygen toxicity. These symptoms vary with oxygen pressure and exposure time and may include varying degrees of physiological symptoms ranging from mild pulmonary reactions, such as a cough, nasal congestion, and occasional ear block to severe convulsions and death. Central nervous system effects are limiting above 304 kPa (44.1 psia), pulmonary effects are most significant between 253 kPa (36.75 psia) and 50.7 kPa (7.4 psia), and long term hematological effects may be important below 101.4 kPa (14.7 psia) and possibly below 50.7 kPa (7.4 psia).

At low oxygen tensions, between 20.7 and 55.2 kPa (3 and 8 psia) the only symptoms reported for continuous exposure of up to 30 days were the appearance of atelectasis with 100 percent oxygen at 34.5 kPa (5.0 psia) and some changes in hematocrit at 55.2 kPa (8.0 psia). Between 55.2 and 103.4 kPa (8 and 15 psia) mild pulmonary symptoms will gradually appear within 12 hours near 103.4 kPa and after several days near 55.2 kPa. The onset of symptoms is gradual and they are completely reversible over 1-3 days. Severe central nervous system symptoms, such as nervousness, increased irritability, twitching and generalized convulsions do not even become evident until oxygen tensions of 241 kPa (35 psia) and higher are reached. Figure 2.2-3 illustrates the onset of oxygen toxicity symptoms with exposure time and pressure (reference 1).

Additional human physiological effects which may be produced by oxygen partial pressures different from sea-level equivalent are changes in vital capacity and total red blood cell mass.

2.3 Diluent Gas

Some investigations have reported that an inert diluent gas is helpful in preventing atelectasis, the collapse of the small air sacs in the lung, which may occur due to absorption of all the oxygen in less-ventilated sacs. There is no clear evidence that nitrogen is unique in its ability to provide this protection; therefore, alternate diluents may be favored if they have engineering advantages.

A diluent gas other than nitrogen is potentially useful in reducing EVA preparation time. Alternate diluents, including helium and neon, have been used regularly in the deep sea diving industry. Some inert gases have lower solubility in the human body than that of nitrogen, and therefore can be washed out to a safe level by less oxygen prebreathing than that required for nitrogen washout. Helium has a lower body solubility, but it also is of much lower density than nitrogen, causing alteration of the human voice, a potential disadvantage for crew vocal communication. Neon has a body solubility lower than that of nitrogen, but its density is similar to that of nitrogen, reducing the voice frequency alteration effect.

Several candidate diluents, including nitrogen, helium, and neon have toxicity limits which are much higher than Earth sea-level pressure. Neon has been used in mixture with helium and oxygen for deep sea diving atmospheres with no harmful effects seen. Argon, krypton, and xenon are toxic at pressures higher than about 69.0 kPa (10.0 psia) (reference 1).

The thermal conductivity of the diluent gas may have a small effect on crew comfort, dependent on the atmospheric pressure, the mixture of gases, and other variables such as air circulation.

2.4 Minor Atmospheric Constituents

A habitable atmosphere contains water vapor and carbon dioxide in small amounts. Water vapor accumulates due to the presence of living organisms and/or the presence of free water in the habitat. Carbon dioxide in the atmosphere is principally due to the presence of living organisms.

On the Space Shuttle, water vapor is controlled between 0.8 and 1.9 kPa (0.12 and 0.27 psia) and carbon dioxide is controlled to a normal upper limit of 1.0 kPa (0.15 psia) for human physiology reasons (reference 4).

Additional trace gases will be present in a habitable atmosphere. Non-toxic, inert trace gases are not of concern when present at low levels because habitat atmospheric leakage can be expected to prevent excessive accumulation. Potentially toxic trace constituents may have to be actively removed to maintain their concentrations within safe ranges.

3.0 Operations, Logistics, and Contingency Considerations and Constraints

The following subsections describe operational factors which may influence the design of the habitat and EMU atmospheres.

3.1 Crew Productivity and Task Performance Capability

High crew productivity is essential to IVA and EVA operations. EVA crew time spent in prebreathing oxygen prior to decompression is basically unproductive, but it may have a positive influence on productivity during the EVA if it allows a lower-pressure, more mobile EMU which induces less fatigue in the crewmembers. Some EVA tasks involving high dexterity and/or mobility may be very difficult to achieve in a high-pressure EMU but relatively easy to achieve in an EMU of lower pressure.

Temporary reductions of habitat internal pressure and accompanying adjustments to the oxygen concentration, like those performed on the Space Shuttle prior to EVA, also reduce crew productivity by consuming IVA crewmember time, while possibly increasing EVA productivity by allowing a lower

EMU pressure. Figure 3.1-1 shows the Space Shuttle EVA preparation timeline, with adjustment of the cabin pressure and composition and oxygen prebreathing by the EVA crewmembers.

If habitat elements contain atmospheres which differ in pressure or composition, crewmember movement between those elements will be slower, degrading IVA productivity. Pressure differences would require airlocks which cause expenditure of crew time in hatch operations and pressure changes and could require prebreathing depending on the pressure difference.

Composition differences at equal pressures would require air movement barriers or hatches. In this case, the extent of the sealing requirement would depend on the significance of the consequences of partial mixing of the two atmospheres due to intermingling during crew passage from one atmosphere to another. Generally, the more stringent the requirement to reduce mixing, the more crew time may be spent in moving from one atmosphere to another.

Crew safety may be affected by the use of airlocks between habitat elements. A safety benefit would arise from the availability of these additional isolatable habitable volumes. A safety disadvantage may be the added time required for crewmembers to move from element to element in contingencies such as solar flares.

3.2 Transfer Between Space Transportation Lander and Outpost Habitat

Reference 5 describes the current operations concept for planet surface systems. It states that initial landings will use an Apollo Lunar Module approach in which crewmembers will require space suits to travel between the lander and the habitation modules. Later, all crew transfers between the lander and the habitation modules will use a pressurized transport module.

Crew transfer between the Space Transportation lander and the surface habitat may involve decompression, dependent on both of their internal pressures and the EMU pressure. If crew transfer is effected by EVA, the EMU pressure will be the driver in the requirement for any crew time spent in decompression preparations. If a portable habitat such as a mobile pressurized module is used for crew transfer, it will probably be of equal pressure with either the lander crew cabin or the surface habitat. The difference in lander and habitat pressures would then determine how much crew time is spent in decompressing.

Common pressures between the lander crew cabin and the surface habitat could eliminate crew transfer decompression time only if a portable transfer habitat is used instead of EVA transfer.

3.3 Noise Level and Crew Verbal Communication

The noise level inside the habitat will be affected by the atmospheric pressure. Lower pressures are expected to necessitate higher volumetric flowrates of air through the thermal control and life support subsystems, resulting in increased fan and air noise. Noise conduction through a thinner atmosphere, however, is reduced; therefore, the net effect of habitat atmospheric pressure on the internal noise level as perceived by crewmembers is uncertain.

Habitat noise levels must be low enough to allow audible caution and warning alarms to be heard by crewmembers in all parts of the habitat. Also, noise levels must not cause degradation of crew productivity due to irritation, sleep disruption, or interference with crew verbal communication (reference 6).

Habitat atmospheric pressure and composition may also affect face-to-face crew verbal communication. Voice efficiency and frequency content are affected parameters (reference 1). Diluents such as helium, which have much lower density than that of nitrogen, produce increased frequency of the voice which, at high helium concentrations, may result in decreased intelligibility (reference 1).

Pressures lower than about 69.0 kPa (10.0 psia) will result in degradation of a crewmember's ability to understand speech transmitted through the atmosphere from a sound source. This was demonstrated by measurements of speech intelligibility during ground-based testing for the Skylab program in a 34.5 kPa (5.0 psia) pressure chamber with ambient noise sources (reference 7).

Speech intelligibility of the Skylab on-orbit crewmembers may have also been affected by facial distortions caused by the zero gravity environment. Misinterpretation of oral statements caused by facial feature distortion associated with micro-gravity environments has been reported to upset some crewmembers (reference 8).

3.4 Consumables Resupply

Logistics considerations of habitat atmospheric pressure and composition include resupply of atmospheric constituent gases. Oxygen and diluent gas must be delivered to the habitat to make up for structural leakage, airlock losses, and contingency habitat decompression. Figure 3.4-1 shows how various habitat internal pressures result in different resupply requirements. This figure is based on an identical habitat design being operated at various pressures. Habitat design requirements can be used to affect the rate of atmospheric gas loss; therefore, the slopes of the curves in Figure 3.4-1 will change based on the requirements which are imposed.

Lower habitat internal pressures result in lower resupply mass requirements. In-situ production of oxygen and/or diluent gas may reduce or eliminate the requirement for regular Earth-based resupply of atmospheric gases.

A given volume of helium has less mass than than equal volume of nitrogen; therefore, the choice of helium as a diluent gas may reduce the mass of atmospheric gas resupply. These savings may be offset somewhat by the fact that the attainment of effective seals in a habitable structure against leakage to vacuum is more difficult with helium than with nitrogen due to the differences in molecular size of the two gases.

Suitable countermeasures for the loss of the habitat gas supply should be determined for possible use in Mars missions where return and/or resupply is not possible.

3.5 Contingencies

Habitat contingency situations may involve movement of the crew from one habitable element to another. Unrestricted passage between the elements is desirable in these instances. A single atmospheric pressure for all elements of the habitat thus is favored from the contingency safety standpoint. Unrestricted movement from the habitat to the EMU for contingency evacuation is also desirable.

Habitat fires will be more easily contained and extinguished in atmospheres which have lower oxygen contents. Higher habitat pressures, coupled with lower cooling air velocities, may reduce the rate of combustion by lowering both the oxygen concentration and the rate of supply of oxygen to a fire in an enclosed space such as an electronics cabinet.

Severe overboard leakage of the habitat atmosphere, in a case such as puncture of the structural pressure shell, results in a pressure decay profile which is determined by the habitat's internal volume, the effective diameter of the leak point, and the habitat pressure control system makeup gas flowrate. Higher initial habitat pressure allows additional time for crew evacuation prior to loss of consciousness, if the oxygen pressure is maintained above the hypoxic limit.

3.6 Airlock Operations Effects on Habitat

One approach to minimization of airlock gas loss is to use the connected habitat as a reservoir for airlock gas during the EVA periods.

For airlocks which use this volume exchange of air with the habitat to depressurize and repressurize the airlock chamber, there will be effects on the habitat pressure during airlock cycling. Air is pumped from the airlock into the habitat during airlock depressurization, increasing the habitat pressure. During airlock repressurization, this air is allowed to flow back into the airlock from the habitat, returning both to approximately equal pressures. The change in habitat pressure may have operational effects on the habitat crew, internal systems, and/or laboratory science, such as delay of experiments in order to schedule them during a period of no pressure changes. Slight to moderate pressure changes should not affect the crew or systems.

The change in habitat pressure in this case is dependent on the ratio of the volume of the airlock to that of the habitat and on the initial pressure of the habitat/airlock. Figure 3.6-1 illustrates the habitat pressure change effect versus initial habitat pressure for volume air exchange with an airlock chamber whose volume is some percent of the habitat volume.

4.0 Laboratory Science Considerations and Constraints

The following subsections describe science experiment factors which may influence the design of the habitat and EMU atmospheres.

4.1 General

Laboratory users who provide experiment packages will experience an increase in requirements for preflight testing and verification of their hardware if habitat pressure less than sea-level is selected. These requirements will be generated by the need for data on science package characteristics related to both total atmospheric pressure and oxygen concentration, such as materials offgassing, flammability, and air cooling. Use of off-the-shelf equipment will be inhibited by increasingly stringent flight requirements at lower atmospheric pressures and/or higher oxygen concentrations.

In addition, ground-based reference experiments should be performed at conditions similar to the planet surface laboratory to reduce the number of experimental variables. This could necessitate reduced-pressure ground facilities or enclosure of planet surface laboratory experiments to raise their operating pressures to sea-level. Commonality of science experiment hardware designs with experiments flown on other space vehicles may be impacted if vehicle atmospheres differ.

Ground-based experiments in high altitude (3000 m/10000 feet) cities might be used as references for habitat experiments at pressures as low as about 69.0 kPa (10.0 psia).

4.2 Life Science

Life science experiments will be affected by habitat pressures and oxygen concentrations different from Earth sea-level. Earth-based experiments are commonly performed with ambient atmospheric pressures near sea-level at 93.1-101.4 kPa (13.5-14.7 psia) and 21 percent oxygen. Laboratory atmospheres different from this will introduce another experimental variable in addition to the difference in gravity and any other parameters being varied.

(Note: Human physiology effects are described in section 2.0 of this report.)

Experimental animal parameters which are known to be affected by habitat pressure and/or oxygen concentration include:

- antibody production (guinea pig),

- susceptibility to viral infection (mouse),
- recovery time from infection (mouse), and
- gas exchange (chicken egg).

Plant parameters which are known to be affected by habitat pressure and/or composition include:

- photosynthesis (wheat, rice, soybean),
- water loss by transpiration, and
- production of toxic gases.

If the planet surface habitat is used to generate life science data under atmospheric conditions significantly different from Earth sea-level, additional ground-based life science research would be required to establish a suitable control database. Development of instruments to measure experimental variables may also be affected by different atmospheric conditions (reference 3).

4.3 Materials Science

Materials science experiments may be influenced by laboratory atmospheric pressure and/or oxygen concentration. The following parameters may be affected:

- use of negative pressure as a method of material containment,
- solubility and/or chemical composition,
- acoustics (reference 3),
- combustion and chemical reactions, and
- heat transfer through surrounding air.

5.0 Habitation Systems Considerations and Constraints

The following subsections describe generic habitat systems factors which may influence the design of the habitat and EMU atmospheres. Various habitable elements may impose some or all of these constraints and considerations. For example, a crew quarters element may have different influences on the habitat atmosphere than those of a food production element. Mission architecture, as reflected in the types of habitable elements on the planet surface, could therefore have an influence on the design of the habitat atmosphere.

5.1 General

All habitat internal hardware and materials will be influenced by the choice of total atmospheric pressure and oxygen concentration. The use of off-the-shelf equipment will be subject to increased preflight testing for habitat atmospheres different from sea-level and/or different from those used in other spacecraft. The following specific parameters are anticipated to be affected:

- materials selection (offgassing, oxidation/corrosion, flammability),
- air cooling of equipment (velocity and density),

- sound levels (noise production from fans and sound transmission),
- certification and verification (preflight testing at operational conditions), and
- commonality with other space programs (equipment design).

Nonmetallic materials selection will be strongly influenced by their flammability characteristics. The history of NASA programs includes the design of habitats for highly enriched or 100 percent oxygen atmospheres. For example, materials utilized for the Apollo program were selected and certified for use in 100 percent oxygen atmospheres. Current flight experience, however, is related to the Space Shuttle program where oxygen concentrations of 30 percent or less are used. No oxygen concentration has been declared as an absolute upper limit for flammability reasons, but design is increasingly difficult beyond 30 to 40 percent oxygen. On Skylab, a 70 percent oxygen atmosphere was used, and nonmetallic materials usage was severely constrained. Crew clothing was made of polybenzimidizole (PBI), a material which was not comfortable for extended wear and was not washable. The walls were anodized aluminum because paints were found to be flammable.

On the Space Shuttle, where a 25-30 percent oxygen atmosphere is used, nonmetallic materials usage is less constrained than it was on Skylab. Paper items such as flight data file documents are designed with non-flammable covers and are stowed when not in use. Velcro is restricted in size and placement to eliminate potential flame propagation paths between Velcro patches. Crew clothing is treated with flame retardant material. Absorbent materials such as towels are placed inside the airlock, a contained area, for drying after use. Electronics are contained in non-flammable enclosures to prevent the spread of a potential fire.

Testing of materials for flammability is carried out by NASA using standards defined in reference 9. Results of this testing are compiled in reference 10. Standard size material samples are used in these tests, and flammability is determined based on the amount of the sample which burns before self-extinguishing. At enriched oxygen concentrations, more materials fail the test and are determined to be flammable at those atmospheric conditions. Atmospheric pressure variation within the range considered in this study is of much less influence on flammability than is oxygen concentration. Table 5.1-1 shows the results of flammability testing on a large number of materials and illustrates the fact that materials selection becomes much more constrained at increasing oxygen concentrations.

Virtually all nonmetallic materials produce toxic products of combustion. In general, the relative toxicity of these products is inversely related to the flammability of the material. Less flammable materials tend to have products of combustion which are more toxic than those of more highly flammable materials.

Compatibility of materials flammability with habitat atmospheric conditions is accomplished in two ways: by design and by operational procedure. Design measures include selection of materials which pass flammability testing, elimination or control of potential ignition sources, enclosure of potentially flammable materials which must be used in the presence of ignition sources, and restriction of potential flame propagation paths. In general, it is not possible to eliminate all potential ignition sources in a long-term crew habitat; therefore, materials selection and containment must be emphasized. Procedural measures, such as stowage of potentially flammable materials when not in use, may also be required.

Offgassing of non-metallic materials is of increasing concern at lower total atmospheric pressures. The partial pressure of the trace gases remains relatively constant in the range of atmospheric pressures considered in this study, but the percent concentration of those gases increases as the total pressure is reduced.

Oxidation of non-metallic materials and unprotected metallic materials is of increasing concern at higher oxygen concentrations. Long-term effects of enriched oxygen content on many materials are not well known, but are potentially serious.

Reduced pressure testing may be required for critical habitat systems, independent of the operational pressure selected, in order to protect against the possibilities of habitat pressure loss contingencies.

Table 5.1-1 Acceptability of Materials for Flammability versus Oxygen Concentration

Oxygen Concentration (percent)	Number of Materials Tested	Number of Materials Passed	Percent Total Population Passed
20.9 (air)	1121	766	55.0
23.8	986	563	40.0
24.5	350	166	29.0
25.9	1504	658	25.7
30.0	1142	654	12.8

Note: Pass/fail acceptance criteria are per NHB 8060.1B.

(Reference 11)

5.2 Life Support

In addition to the general effects described in section 5.1, habitat atmospheric pressure and composition may affect life support subsystem hardware and operations in the following ways:

- Plant growth for life support and/or food production may be affected by the habitat atmospheric pressure and composition in several ways. Photosynthesis, transpiration, and release of toxic gases all vary in relation to pressure, oxygen concentration, or carbon dioxide concentration. Carbon dioxide concentration has an effect on plant growth, with enriched carbon dioxide/low oxygen concentration atmospheres producing higher photosynthesis rates (reference 12). Wheat germination and early growth under atmospheric pressures as low as about 6.0 kPa (0.87 psia) have been shown (reference 13). In this experiment, seedling characteristics such as leaf size and chlorophyll content were significantly lower than those of control seedlings grown under Earth atmospheric conditions. Germination rate was significantly lower except when the atmosphere was composed of 99.1 percent oxygen. Oxygen is required for wheat germination and growth during its pre-photosynthetic phase.

- Microorganism activity, ecology, and population dynamics may be affected by habitat atmospheric pressure and composition (reference 14).

- Food crop animal growth may also be affected by habitat atmospheric pressure and/or composition. Known effects on laboratory animals are described in section 4.2 of this document.

- Resupply of life support atmospheric gases will be affected by habitat atmospheric pressure and composition. Higher pressures will result in increased gas losses through leakage and will demand more gas storage for contingency depressurization and repressurization of the habitat. The amount of oxygen and diluent storage required will be affected by the composition of the internal atmosphere. Airlock gas recovery based on pumping the airlock gas should achieve the same final airlock pressure independent of its initial pressure; therefore, gas loss from the airlock should be independent of habitat pressure. Resupply of life support oxygen and/or diluent gas by processing of planetary soil could be used to reduce or eliminate normal Earth-based resupply requirements.

- Control of the oxygen concentration in the habitat atmosphere becomes more critical at extremely low habitat pressures because human physiological requirements and materials flammability constraints combine to produce a more narrow band of allowable conditions. In some cases, this results in a controllability issue, resulting in more stringent requirements on life support sensors and control systems at lower habitat pressures.

- Fire suppression becomes more difficult at increased oxygen concentrations. More inert gas must be used to reduce the local oxygen concentration around a flame to a level which cannot sustain combustion. In extreme cases, the amount of fire extinguishant gas required becomes large enough to create a significant change in habitat atmospheric pressure and composition.

Test data on fire extinguishment by halon 1301 as function of oxygen concentration show that the required amount of halon increases rapidly with oxygen concentration. Halon in this test was insufficient for fire extinguishment above 60 percent oxygen at 55.2 kPa (8 psia). There was some evidence of halon exploding when used on a strongly burning fire in 80 percent oxygen (reference 15).

Test data in 100 percent oxygen and Earth gravity show that gaseous extinguishants (halon 1301, carbon dioxide, nitrogen, argon, and helium) intensify burning by stirring up the fire. Water, foam, and an aqueous gel were found to be good extinguishants. Solids (sodium and potassium bicarbonate) and venting to 0.83 kPa (0.12 psia) in 2 min were ineffective in fire extinguishment (reference 16). Venting was also tested and found to be ineffective in Skylab experiment M479 on microgravity combustion.

- It is assumed that a preintegrated habitat pressure vessel would be launched from Earth at an initial internal pressure approximately equal to or higher than sea-level to prevent negative pressure loads (external pressure higher than internal pressure) on the structure. For operational pressures less than sea-level, this necessitates the reduction of habitat atmospheric pressure at some point after launch, resulting in requirements for pressure reduction controls and procedures.

- Life support subsystem heat exchangers for removal of atmospheric humidity will tend to over condense the humidity at atmospheric pressures substantially lower than 70.3 kPa (10.2 psia). An additional non-condensing heat exchanger or water spray rehumidifier may be required at low habitat pressures (reference 17). Heat exchangers designed specifically for planet surface habitats will not necessarily have this tendency.

5.3 Thermal Control

In addition to the general effects described in section 5.1, habitat atmospheric pressure and composition may affect thermal control subsystem hardware and operations in the following ways:

- Cooling fan power, and potentially its size, must be increased at reduced atmospheric pressures in order to maintain equal mass flowrate. A similarity analysis shows that the fan power requirement is inversely proportional to the square of the total habitat pressure (reference 17). With no other changes to the system, the fan power will double from about 500 W to about 1000 W with a pressure drop from 101.4 kPa to 71.7 kPa (14.7 psia to 10.4 psia), respectively. No attempt was made in this analysis to optimize duct or water loop sizing (reference 18).

- Mass and volume of air cooling components such as fans, ducts, and filters are increased at reduced atmospheric pressures in order to maintain equal pressure drop with the increased volumetric flowrate. In general, the thermal control system would not have to physically change greatly if the habitat could afford the extra fan power. If, however, power was relatively expensive, the fan power increase could be minimized by impacting the mass of the system.

5.4 Health Care

In addition to the general effects described in section 5.1, habitat atmospheric pressure and composition may affect health care subsystem hardware and operations in the following ways.

Health care systems will be used to monitor the health status of individual crew members and to treat resultant medical problems. Health care systems will provide capability to measure and monitor physiologic variables associated with work capacity, lung function, blood chemistry, tissue oxygenation, immune system function, and other physiologic functions affected by respirable atmosphere. Effects of changes in respirable atmosphere pressure or composition during a mission expected to be investigated during mission planning and design phases, will be monitored during a mission as part of health care systems operations. Examples of changes to which a crew member(s) may be subjected that may affect long term health, ability to perform immediate tasks, or survival are changes in pressure, oxygen concentration, carbon dioxide concentration, (inert) diluent gas concentration, dust or particulate material, temperature, and water vapor upon moving from one mission task or element to another.

Countermeasures for known or potential deficiencies in respirable atmosphere design will be incorporated in health care systems. For example, prebreathe protocols and monitoring instrumentation will be provided if needed to minimize risk of decompression sickness and related disorders due to transition from the (normal) ambient pressure to a significantly lower pressure. To assist adaptation to respirable atmosphere pressure and/or composition changes within habitable pressurized volumes, adaptation protocols and monitors may be developed as part of technology or advanced development projects. Areas within planet surface habitats or vehicles having special dust, humidity, or gas composition control will be provided if necessary to meet crew health needs.

Medical care will include capability to rescue and resuscitate a crewmember(s) incapacitated by a problem with a respirable atmosphere, to deliver oxygen therapy, ventilatory support, and fluid therapy, to perform emergency surgery, and to provide intensive care, hyperbaric treatment, and (outpatient) respiratory therapy. Medical diagnostic and monitoring capabilities will be provided consistent with treatment capabilities. Medical diagnostic and treatment protocols will be developed as part of technology and advanced development projects.

Baseline data will need to be collected which will be used to differentiate normal physiologic adaptation to an abnormal environment from intrinsic pathophysiology. Some terrestrial practices will need to be modified, for example, standard hyperbaric treatment tables for decompression sickness assume return of the hyperbaric chamber occupants to 101.4 kPa (14.7 psia) at the conclusion of the treatment. If further decompression to a lower habitat pressure will take place, then somewhat different procedures will be required.

5.5 Crew Accommodations

In addition to the general effects described in section 5.1, habitat atmospheric pressure and composition may affect crew accommodations subsystem hardware and operations in the following ways:

- potential fan size and power increases,
- design of consumables packaging,
- food cooking temperature and time.

Fans used in crew accommodations hardware, such as the shower and the waste management compartment, may have to be increased in size and power for habitat pressures less than sea-level. Air movement applications which are sensitive to the mass flowrate of air would require more fan power and potentially larger fans at lower habitat pressures.

The design of packaging for crew consumables such as food is also affected by the difference between Earth sea-level pressure and habitat pressure. If a sea-level facility is used for packaging consumables for launch, the trapped air will exert pressure on the packaging materials when exposed to a lower habitat pressure. Some foods can be vacuum-packed, preventing this effect, but other foods, such as bread, cannot be vacuum-packed without destroying their palatability. Frozen foods, also, are packaged with an air-filled ullage space.

Earth-based food packaging for habitat pressures much lower than sea-level could require construction of a food production and packaging facility on Earth which is at the habitat pressure. Foods would then be produced, packaged, transported, stored, and used at the same ambient pressure. Such a food production facility would be specialized and therefore expensive to construct and operate.

Lower habitat pressure lowers the boiling point of water and substances. The reduced pressure impacts food recipes and increases cooking times. The relationship of cooking time to temperature is food-dependent. For cooking of in-situ produced food, crew time required for food preparation will increase with lower habitat pressures, potentially affecting IVA crew productivity. Pressure-cooking of some foods can reduce preparation times by cooking inside a pressurized container

The relationship of habitat pressure to the boiling point of water is shown in Figure 5.5-1. Prepared food items are heated below the boiling point of water and served around 60 degrees C (140 degrees F), which deters the growth of microorganisms. Food-borne illness is caused by microorganisms and is a chief concern for the health and safety of the crew. All microorganisms are killed by heat, if the temperature is high enough and is applied for a sufficient length of time. The relationship of destruction time to temperature is microorganism-dependent. The destruction temperature ranges from 60 degrees C (140 degrees F) for vegetative bacteria to 121.1 degrees C (250 degrees F) for heat-resistant spore-forming bacteria (reference 19).

5.6 Structures and Mechanisms

In addition to the general effects described in section 5.1, habitat atmospheric pressure and composition may affect structures and mechanisms subsystem hardware and operations in the following ways:

- Pressure vessel design requirements may be more severe for higher pressure of the internal atmosphere, e.g. seals around penetrations will be subject to higher loads and will be designed to closer tolerances to reduce leakage. In this instance, higher internal atmospheric pressure produces more exacting design requirements.

- Pressure vessel mass may be affected by internal pressure in some cases, e.g. the pressure vessel minimum thickness requirement is related to internal atmospheric pressure, but other considerations such as launch and landing loads may drive the thickness. In the case that internal pressure becomes a pressure vessel wall thickness driver, increased pressure results in a higher structural mass. An analysis from reference 8 showed that regolith overburden and launch loads are more stringent factors for pressure shell thickness than is internal pressure, as illustrated in Figure 5.6-1.

- Use of the habitat internal atmospheric pressure as a means of structural stiffening for launch and landing may be beneficial in terms of mass savings. In this case, higher internal pressure may produce additional stiffening and result in some additional mass savings.

- Habitat elements at different pressures would require airlocks between them, resulting in an increased amount of structure. In this case, differences in element atmospheric pressures result in increased structural mass.

5.7 EVA Accommodations

In addition to the general effects described in section 5.1, habitat atmospheric pressure and composition may affect EVA accommodations subsystem hardware and operations in the following ways:

- Prebreathe apparatus will not be required if habitat pressure is designed to yield an R value to enable zero prebreathe EVA operations at physiologically acceptable levels.

- Airlock gas losses during depressurization will not be affected by habitat pressure since the final pressure before evacuation is dependent on the depressurization pump technology and not on the initial pressure. During normal pressure operations, the airlock and all other habitable volumes will leak less gas to the outside environment at lower pressures.

- Airlock pump mass, volume, and power are not significantly impacted by initial airlock pressure. The airlock pump design is driven by the final pressure before evacuation. Power expended during the initial stages of depressurization is very low compared to the power expended when the airlock pressure reaches low values such as 3.4-6.9 kPa (0.5-1.0 psia).

6.0 Extravehicular Mobility Unit Considerations and Constraints

The following subsections describe EMU systems factors which may influence the design of the habitat and EMU atmospheres.

One of the primary purposes of establishing a manned Lunar or Mars base, if not the primary purpose, is to allow exploration via regular, extensive, routine EVA on the surface. This EVA will be used to perform science on the surface which cannot be performed in any other way. Because of the importance of EVA, its extent, and its expense, it is vital to maximize the productivity of the EVA crew. Equipment and tool design must be compatible with EVA operations. Crews must be properly trained in well-designed operations (techniques and procedures). Crews must be able to dedicate maximum time to useful, productive tasks and minimum time to ancillary, support tasks (such as EMU servicing). Finally, the EMU must be designed and constructed to allow the crew to be as productive as possible with minimum fatigue.

6.1 General

In general, it has been determined that an EMU may be designed to eliminate potential ignition sources within the space suit enclosure. Due to this, materials flammability is less of a concern than it is for the habitat.

In order to optimize EVA productivity, we wish to minimize, or if possible, eliminate the ancillary task time of pre-EVA denitrogenation characteristically identified as prebreathing operations. Nitrogen bubbles may form in the body of an EVA crewmember, causing dangerous dysbarisms if certain ratios of suit pressure to habitat pressure are not maintained. Denitrogenation, to prevent these problems by flushing nitrogen from the crewmember's system, may be accomplished before conducting an EVA by prebreathing oxygen. This process will cause nitrogen in the body to be replaced by oxygen which will not cause decompression sickness.

The goal is to reduce the partial pressure of nitrogen dissolved in the body tissues to a value such that there is no risk of decompression sickness during an EVA. The ratio of dissolved nitrogen partial pressure to ambient pressure is known as the Bends Ratio "R" value. Ideally, it is desired to have R less than 1.22 since few if any dysbarisms will occur at this point. This however poses severe problems for EVA suit design. For a 101.4 kPa (14.7 psia) cabin with 79 percent nitrogen content, the partial pressure of nitrogen is 80.0 kPa (11.6 psia). This means that for R=1.22 the suit pressure must be no less than 65.6 kPa (9.5 psia). Because of various suit design-related technology limiting factors to keep suit pressure below the current 57.2 kPa (8.3 psia) limit, the 65.6 kPa pressure level is currently unacceptable.

A compromise can be reached however by allowing R values greater than 1.22. This is the approach currently used on the Space Shuttle where an R of 1.65 is used and was initially the plan for Space Station Freedom where a value of 1.4 was specified and was originally to be met by the use of a 57.2 kPa (8.3 psia) EMU. Figure 6.1-1 shows a family of curves of relevant habitat pressures versus suit pressures as influenced by bends ratio. With an R=1.4, suit pressure can be as low as 36.5 kPa (5.3 psia) without prebreathe, assuming a habitat pressure of 70.3 kPa (10.2 psia).

An R=1.2 has been suggested as being a more reasonable maximum value for Lunar and Mars EVA. Based on Figure 6.1-2, with an R=1.2 and habitat pressure of 70.3 kPa (10.2 psia), an EVA suit pressure of 40.0 kPa (5.8-6.0 psia) would be adequate to still maintain a zero-prebreathe capability.

6.2 Space Suit

As discussed in section 3.1, EVA crew productivity is related to the space suit atmospheric pressure. Increased suit pressure results in crewmember fatigue and lower productivity. Gloved hand fatigue is especially noticeable by EVA crewmembers.

Unlike the zero gravity conditions experienced in Earth orbital operations, the partial gravity conditions on planetary surfaces produce a kinesthetic and sensory perception of "up and down" as well as weight. Contrary to the free-floating conditions of zero gravity and the lack of awareness of EMU weight as such, the weight factor in the partial gravity environments serves as a disadvantage. It burdens the astronaut with the weight of carrying the EMU hardware necessary for traversing, exploring, and working on these planetary surfaces. Another major issue that strongly affects the weight and design of future space suits and portable life support systems is the operational pressure chosen for the EMU.

The most straightforward method of increasing crewmember productivity and decreasing crewmember fatigue is to lower the suit pressure as much as possible. With current technology, (especially concerning EVA gloves), we are confined to a suit pressure of 57.2 kPa (8.3 psia) or less. In general, from an EVA standpoint we prefer it to be less, in fact we prefer that it be in the neighborhood of 29.6 kPa (4.3 psia). At this pressure, current suits and gloves yield excellent mobility and dexterity and maximize productivity. As pressure increases, productivity falls off markedly. Figure 6.2-1 shows an example of mobility joint degradation due to increasing pressures. At 29.6 kPa (4.3 psia) the crewmember also has a good breathing atmosphere for performing heavy labor and suitable for ventilation and cooling purposes. It also provides an emergency minimum suit pressure at 25.5 kPa (3.7 psia).

6.3 Portable Life Support

There are several factors to consider in choosing an operating pressure for an EMU. The first factor deals with oxygen toxicity. One approach to avoiding potential oxygen toxicity even with a high pressure suit is with a passive mixed gas suit, a suit that is sealed with a gas mixture having an Earth normal oxygen pressure but in which all makeup gas is oxygen. Figure 6.3-1 shows the oxygen tensions that would normally be encountered using such a suit during an EVA for EMU leakage rates of between 40 and 400 cc/minute for EMU's with 57.2-65.5 kPa (8.3-9.5 psia) operating pressures. Figure 6.3-1 also shows how these various oxygen tensions would relate to oxygen toxicity symptom onset.

A more complex way in which to totally ensure against oxygen toxicity is to develop a two-gas system in which the use and leakage makeup is accomplished not by 100 percent oxygen, but by a two-gas configuration such as oxygen and nitrogen. This method is somewhat more complicated than a one-gas system. Oxygen replacement by itself can be accomplished quite easily with a standard pressure regulator which is well within the state of the art capability. Because the suit is generally donned in a sea-level environment, the preexisting nitrogen makeup is widely acceptable for the duration of the EVA even with suit leakages taken into account. The two-gas system, on the other hand, would require continuous monitoring of the oxygen partial pressure and the regulation of both oxygen and nitrogen in order to maintain the proper oxygen tension. Furthermore, this method is impractical because it is well known that the advanced regenerable technologies are constantly fighting a weight and volume issue. Generally, systems that must utilize non-expendables have been found to be heavier and bulkier than those systems which "throw away" resources to accomplish thermal and carbon dioxide control during EVA. Therefore; the use of a two-gas system is impractical for planetary surface systems because of the added weight and volume associated with another gas (nitrogen) and the added complexity associated with the oxygen monitoring and subsequent nitrogen control.

For EVA's of six to eight hours, 100 percent oxygen can be used at pressures up to 41.4 kPa (6.0 psia) with absolutely no risk. Recent investigations suggest that it may be acceptable to use 100 percent oxygen for pressure suits at pressures as high as 65.5 kPa (9.5 psia).

7.0 Integration of Considerations and Constraints

The following subsections describe all the investigated parameters which may influence the atmosphere design and the ways in which those parameters interact to reinforce or negate each other.

7.1 Compilation of Investigated Parameters

Table 7.1-1 lists the parameters which have been investigated as part of this study. Along with each parameter, the effect of the variation of atmospheric pressure and/or the effect of variation of oxygen concentration is described. Methods for expansion of the allowable habitat pressure range are postulated.

Table 7.1-1 Investigated Parameters which are Useful in the Design of Habitat and EMU Internal Atmospheric Pressures

Parameter	Expected Effects	Methods for Reducing Impact of the Effects
Human Physiology		
Hypoxia	Oxygen pressures significantly below sea-level equivalent induce hypoxia	Acclimatize crew over long duration to somewhat reduced oxygen pressure
Oxygen Toxicity	Oxygen pressures significantly above sea-level equivalent induce symptoms of oxygen toxicity over time	Shorter missions and/or lower oxygen pressures
Decompression Sickness	Reduction of atmospheric pressure with dissolved diluent gas in the body results in evolution of gas bubbles in body tissues	Reduce the partial pressure of diluent gas in the habitat atmosphere, prebreathe 100 percent oxygen to reduce dissolved gas prior to decompression, decompress over a longer period of time, or decrease the pressure difference between the habitat and EMU.
Operations and Logistics		
EVA Prebreathe Time	Lower maximum acceptable R values increase prebreathe time, impacting mission operations	Reduce prebreathe time by use of diluent with faster tissue wash-out and/or reduce initial diluent/EMU pressure ratio (R)
EVA Crew Performance	Higher EMU pressure causes increased fatigue	Increase suit and glove mobility
Crew Movement Between Habitat Elements	Differences in element atmospheres create need for airlocks between elements	Design habitat for all elements at same atmospheric pressure and composition
Transfer Between Lander and Habitat	Decompression time may be required if lander and habitat are at different pressures or if EVA used as means of	Design lander cabin and habitat with equal atmosphere pressures and compositions and use a portable habitat module as means of crew transfer

	transfer	
Habitat Noise Level	Increased fan noise at lower pressure	Develop quiet fans and reduce air cooling requirements by coldplating electronics
Crew Verbal Communication	Voice efficiency and frequency affected by reduced atmosphere pressure (<69 kPa)	Use wireless communication if necessary in habitat to reduce reliance on face-to-face vocal communication
	Voice frequency affected by reduced diluent gas density (e.g. helium)	Electronic processing of voice communications to reduce frequency distortion caused by diluents such as helium
Logistics	Higher habitat pressure causes increased gas loss	Increase airlock gas recovery percentage, reduce habitat structural leakage, produce make-up gases in-situ
Fire Contingency	Higher habitat oxygen concentration increases combustion rate	Use inert atmosphere in uninhabited portions of habitat (e.g. electronics bays) or encapsulate electronics
	Lower habitat pressure increases air flowrate for electronics cooling, resulting in increased combustion rate	Use coldplate cooling of electronics
Laboratory Science		
Preflight Testing	Higher habitat oxygen concentration increases the requirements for experimental equipment safety testing	Enclose experiments in special containers in lab
Ground-Based Experiments	Habitat pressure or oxygen concentration different from Earth sea-level may introduce experimental variable	Perform ground experiments at habitat-equivalent atmosphere, enclose lab experiments in special containers
Use of Off-the-Shelf Equipment	Habitat pressure or oxygen concentration different from Earth sea-level reduces the use of off-the-shelf equipment	Enclose lab experiments in special containers when operating
Life Sciences (Animal and Plant Experimentation)	Habitat pressure or oxygen concentration different from Earth sea-level may introduce experimental variables by affecting animal/plant physiology	Enclose lab experiments in special containers
Materials Sciences	Habitat pressure or oxygen concentration different from Earth sea-level may introduce experimental variables by affecting physical and/or chemical conditions	Enclose lab experiments in special containers
Habitation Systems		
	Higher habitat oxygen concentration increases the flammability of many	Select habitat materials based on design oxygen concentration

	materials	
Materials Selection	Lower habitat pressure may increase offgassing from materials	Select habitat materials based on design pressure
	Higher habitat oxygen concentration may increase oxidation of materials	Select habitat materials based on design oxygen concentration
Air Cooling	Lower habitat pressure reduces convective heat transfer coefficient and natural convection	Design equipment for habitat pressure, use coldplate cooling
Test and Verification	Habitat pressure different from sea-level increases complexity and cost of preflight performance and certification testing	Implement previous program experience base for performance and certification testing
Use of Off-the-Shelf Equipment	Habitat pressure or oxygen concentration different from Earth sea-level reduces the use of off-the-shelf equipment	Adapt off-the-shelf equipment to meet habitat safety and operational criteria.
Life Support		
Plant Growth	Increased oxygen concentration may reduce plant growth rates.	Perform research in plant growth under non-sea-level conditions.
Animal Growth	Reduced habitat pressure may affect animal growth.	Perform research on animal growth under non-sea-level conditions.
Rehumidification	Low habitat pressure may require means for rehumidification of the air.	Design life support subsystem for selected habitat pressure.
Thermal Control		
Mass/Volume/Power	Lower habitat pressure increases cooling air system mass and volume and/or power, depending on the design approach	Optimize the air cooling system for the habitat pressure
Health Care		
Medical Countermeasures	Habitat pressure and/or composition different from Earth sea-level may require increased medical monitoring and countermeasures	Perform physiological research to determine points at which changes in atmospheric parameters produce adverse effects in humans
Crew Accommodations		
Fan Power	Lower habitat pressure increases cooling fan size and power requirements to achieve equal cooling	Design equipment for coldplate cooling
	Habitat pressure lower than	Develop reduced-pressure packaging facility on

Consumables Packaging	sea-level causes packages sealed at sea-level pressure to experience pressure differential	Earth, design packaging to accommodate pressure differential, develop crew procedures for dealing with packages
Food cooking time	Lower habitat pressure reduces the boiling point of water, increasing cooking time for some in-situ produced foods	Develop special cooking utensils, e.g. pressure cookers, for some foods
Structures and Mechanisms		
Pressure Shell Mass	Lower habitat pressure may reduce pressure shell mass only if other factors, such as regolith shielding and launch/landing loads, do not drive the mass	Demonstrate that habitat pressure is not the driver for pressure shell mass
EVA Accommodations		
Airlock gas recovery	Lower habitat pressure reduces the amount of energy required to recover airlock gas during airlock depressurization	Develop more efficient gas recovery systems
Extravehicular Mobility Unit		
Space Suit Mass	Lower EMU pressure enables reduction of suit mass	Incorporate high strength / light weight materials and composites
Space Suit Mobility	Lower EMU pressure increases space suit mobility	Develop new space suit and glove technologies which increase mobility
PLSS Mass	Lower EMU pressure reduces the potential need for a two-gas PLSS, resulting in lower PLSS mass	Reduce EMU gas leakage to maintain an initial charge of habitat atmospheric diluent in the EMU. This may be impractical. Even with minimum leakage, a two-gas EMU will still need a complex monitor and control device.

7.2 Selection Space

An integrated map of potential habitat and EMU atmospheres is shown in Figures 7.2-1 through 7.2-4. Each figure is predicated on selection of a particular value for the decompression ratio, R. The time relationship between R values may be seen in Figure 7.2-5, which shows how R is reduced as EVA crewmembers breathe 100 percent oxygen prior to decompression, washing nitrogen out of their body tissues.

Figure 7.2-1 is based on R=1.0. This value for R eliminates the potential for decompression sickness for normal operations. It is therefore the lowest R value considered in this study, but lower R values have been used in programs such as Apollo/Skylab (see section 1.2).

Figure 7.2-2 is based on R=1.22. This value for R reduces the statistical occurrence of serious decompression sickness to 0.3 percent per crewmember per EVA (reference 2), and is therefore considered safe for long-term, remote missions with multiple EVA's, such as planet surface scenarios.

Figure 7.2-3 is based on R=1.4. This is the value of R which has been baselined for the Space Station Freedom program. It results in a statistical occurrence of serious decompression sickness of 1.1 percent, based on ground testing.

Figure 7.2-4 is based on R=1.67. This is the near the value of 1.65 used by the Space Shuttle program. An R=1.65 results in a statistical occurrence of serious decompression sickness of 4.7 percent based on ground testing.

7.3 Strategic Options

Several design and operational strategies can be described for accommodating the needs of the habitat and its science users as well as the need for EVA. Each strategy has advantages and disadvantages in terms of habitat and EMU development and operations costs, launch mass and volume, and crew operations.

One option is a dual-pressure habitat, with the laboratory at sea-level atmospheric pressure and composition and the remainder of the habitat at reduced pressure. The R value between the two habitat pressures and the R value between the reduce-pressure habitat and the EMU could be selected to eliminate the need for crew prebreathe prior to either decompression, but crewmembers exposed to the sea-level pressure would be required to remain in the reduced-pressure habitat for an extended period prior to performing an EVA. Figure 7.3-1 illustrates the differences in atmospheric pressure and composition between the habitat elements. The airlock between the laboratory and the reduced-pressure habitat could be much simpler than an EVA airlock because it would not have to support dust removal, EMU checkout and storage, or hyperbaric treatment. The advantages and disadvantages of the dual-pressure habitat approach are listed in Table 7.3-1.

A second option is the use of a dual-pressure EMU. An R value which eliminates crew prebreathe prior to EVA could be selected. EMU pressure could later be reduced toward the end of the EVA period to increase crewmember mobility. Table 7.3-2 describes the advantages and disadvantages of this strategy.

A third option is to accept crew prebreathe as a part of EVA preparation. This results in reduced IVA crew productivity and has the potential for reduced EVA crew productivity if fatigue is induced by excessively long pre-EVA procedures. Table 7.3-3 describes the advantages and disadvantages of this option.

Relaxation of the materials flammability constraint is a fourth option for expanding the envelope available for atmosphere design. Figure 7.3-2 illustrates the effect of increasing the oxygen concentration from 30 percent to 50 percent at R=1.22. It should be remembered that increased oxygen concentrations have additional effects besides materials flammability, as described in Table 7.1-1. The reduction in the number of materials available for habitat equipment design at enriched oxygen concentrations may outweigh the benefits of this approach. Table 7.3-4 describes the advantages and disadvantages of this approach.

Table 7.3-1 Advantages and Disadvantages of Dual-Pressure Habitat

Advantages:

- Increased crew productivity due to zero prebreathe for EVA
- Sea-level pressure for the laboratory to allow experimentation at conditions similar to Earth-based research
- More than one isolatable pressurized element for pressure-loss or fire contingencies

Disadvantages:

- Added structure and systems for airlock between habitat and laboratory

- Decreased crew productivity resulting from need to transfer through airlock between habitat and laboratory
- Increased design complexity for reduced-pressure habitat (e.g. enriched oxygen effects on materials selection)
- Potential safety issue for rapid crew evacuation of an element

Table 7.3-2 Advantages and Disadvantages of Dual-Pressure EMU

Advantages:

- Allows a progressive decrease in suit pressure with EVA time, allowing greater mobility at the end of the EVA

Disadvantages:

- Increased EMU design complexity for higher pressure capability and for pressure change capability
- Loss of some EMU gas when suit pressure reduced
- EVA mission timelines would need to be adjusted to limit the duration of activities which require the lower suit pressure in order to prevent dysbarisms. Timelines may also need to be adjusted to place all low suit pressure activities toward the end of each EVA since prebreathe would actually be accomplished during the initial hours of the EVA when operating at the higher pressure level
- The first decompression in staged decompressions should not exceed 1.0; therefore, the initial suit pressure would have to be equal to the habitat diluent pressure.

Table 7.3-3 Advantages and Disadvantages of EVA Crew Prebreathe

Advantages:

- Allows sea-level habitat and low pressure EMU with attendant reductions in design complexity
- Allows sea-level laboratory experimentation for comparison to Earth- based science
- Requires no extra airlocks between habitat and laboratory

Disadvantages:

- Reduces IVA crew productivity due to time required for prebreathe protocol
- May preclude quick-egress EVA capability for mission success reasons due to decompression sickness risk (still available for crew safety contingencies but would run the risk of decompression sickness during emergency evacuation)
- Potential for reduced EVA crew productivity if prebreathe time is excessive and fatiguing to the crewmembers
- Requires additional hardware support elements if mask breathing used

Table 7.3-4 Advantages and Disadvantages of Relaxing Flammability Constraint

Advantages:

- Allows normoxic atmosphere at lower habitat pressure
- Lower EMU pressure allowed
- Attendant reduction of EMU design complexity
- Maintains sea-level habitat pressure with attendant reduction in design complexity and power use due to air cooling requirements

Disadvantages:

- Reduced materials selection due to higher oxygen concentration
- Oxygen toxicity constraint reduces the usefulness of this strategy in some cases

8.0 Conclusions and Recommendations

8.1 Habitat and EMU Atmosphere Design Space

Figure 8.1-1 shows the integrated set of atmosphere design envelopes defined by this study. The major constraints which bound the integrated design region are human physiology (hypoxia and oxygen toxicity) and materials compatibility (flammability). Earth sea-level pressure was used as an upper limit of consideration for the habitat pressure.

A sample set of important design variables for habitable element atmospheres is shown in Table 8.1-1. The list in Table 8.1-1 could easily change when considerations for a permanent planet surface outpost such as plant growth, food preparation, and long-term materials oxidation are better understood. The relative priority of each consideration is in some cases dependent on the mission architecture and the scope of activities allocated to the habitable elements.

8.2 Need for Level II / III / IV Planning

The Lunar/Mars exploration program should develop a method for evaluating the considerations which influence the habitat and EMU atmosphere design. This method could include quantification of the impacts of various atmosphere designs, based on a reference baseline atmosphere.

Prioritization of the atmosphere design considerations and constraints should be made in the context of the mission objectives and architectures. For instance, a mission which defines regular and frequent planetary exploration by EVA as its major objective might produce a different set of priorities than would a mission which has laboratory life science experimentation as its primary goal.

Additional program elements, including the Space Station Freedom and Lunar/Mars Space Transportation must be considered for their potential effects on the planet surface habitat and EMU atmospheres. Figure 8.2-1 illustrates the potential interfaces between crew habitats and EMU's across the Lunar/Mars program. One issue is the possible use of the surface EMU for zero-gravity EVA during interplanetary transport. If it is used in this manner, this provides a further input to the selection of PSS habitat and EMU atmospheres.

8.3 Need for Research and Technology Development

Additional research should be performed into the human physiology effects of various atmospheric pressures, oxygen concentrations, diluent gas types, and decompression ratios to expand the envelope of unconstrained atmosphere designs. Extended duration testing should simulate long-term Lunar and Mars missions.

Materials research, development, and testing should be increased to develop broader knowledge of the flammability, offgassing, and oxidation effects of various atmospheric pressures and compositions in reduced gravity. New materials which can be used in enriched oxygen environments should be developed.

EMU technologies, especially those applicable to the design of higher pressure space suits, gloves, and life support subsystems, should be developed to increase the efficiency with which crewmembers move from habitat to EMU and to increase the capabilities of the suited crewmembers.

Life support technology development should include investigation of the effects of atmospheric pressure and composition on potential biological components of a closed ecological life support subsystem, such as plants, animals, and microorganisms.

Crew accommodations technologies should be developed to support food, clothing, consumables packaging, and interior outfitting systems which expand the envelope of potential habitat atmosphere designs.

8.4 Conditional Conclusions and Recommendations

This section summarizes some potential recommendations, based on incomplete information about Lunar and Mars program goals and mission plans. It is expected that situations not foreseen by the following conditional recommendations will arise. In this case, additional study is clearly required to make recommendations for each specific situation.

Conditional Statements Based on Potential Program Goals and Architectures:

If program goals and mission architecture emphasize EVA exploration of the planet surface, then mission productivity can be significantly enhanced by reducing or eliminating oxygen prebreathe by the EVA crew. In combination with 1991 EMU technology and physiological knowledge, this would result in a 40.3 kPa (5.85 psia) EMU pressure, an R value of 1.22, and a habitat pressure of 69.0 kPa (10 psia) with 30 percent oxygen.

If program goals and mission architecture emphasize Lunar surface life science as a means of preparation for human trips to Mars, then science data comparison with Earth-based control experiments may drive a requirement for a sea-level atmosphere in the habitat. This would result in a 101.4 kPa (14.7 psia) habitat pressure with 21 percent oxygen, an R value of 1.22, and an EMU pressure of 65.6 kPa (9.5 psia).

If both surface exploration and laboratory life sciences are important mission goals, then one way of accommodating both goals, eliminating the impact on crew productivity of oxygen prebreathe, and utilizing 1991 EMU technology is to partition the habitat into two pressure zones, as described in section 7.3.

If long-term crew stays are desirable for program/architectural reasons, then the requirement for acceptable crew living conditions drives down the maximum feasible oxygen concentration to allow a wider diversity of habitat materials without an undue flammability hazard. A 30 percent oxygen concentration is a reasonable upper limit in this case.

If very short crew stays are planned, then oxygen pressure may be varied from Earth sea level equivalent without undue oxygen toxicity or flammability concerns. A 34.5 kPa (5.0 psia) habitat pressure with 100 percent oxygen has been demonstrated by the Apollo program. In this case, R=0, and EMU pressure is independent of habitat pressure from a physiological standpoint.

If a program goal is to establish a Lunar outpost at minimum cost, then reductions of operational crew productivity may be acceptable in return for lower habitat and EMU development costs. In this case, habitat pressure would be 101.4 kPa (14.7 psia), EMU pressure would be 5.85 psia, and R=1.22 could be achieved by about 4 hours of 100 percent oxygen prebreathe prior to each EVA.

If a program goal is to develop an evolutionary surface habitat to accommodate various program phases, then the habitat elements should be designed to operate over a range of pressures. (e.g. utilize lower pressure initially during a construction and EVA surface exploration phase, then utilize sea level pressure during a Mars mission simulation/life science phase.)

Conditional Statements Based on Potential Systems Engineering Situations:

If planet surface resource extraction provides oxygen and/or diluent gas for the habitat and EMU atmospheres, then resupply logistics becomes a less severe driver for the systems design, and higher habitat internal pressures have less associated logistics penalty that they do in the case of Earth-based resupply of all atmosphere gases.

If only the EMU technology available in 1991 (55 kPa/8 psia) is available for the planet surface EMU, then 83 kPa (12 psia) is approximately the highest habitat pressure which can be selected while maintaining a zero prebreathe condition and an R value of 1.22 with a 57.2 kPa (8.3 psia) EMU. This 1991 technology EMU would not be acceptable in Mars gravity due to its weight.

If EMU technology evolves through steady funding over the time frame of PSS program development, then EMU pressure may not be an influence on habitat pressure. (Evolutionary EMU's may have a high pressure capability which allows zero prebreathe from a sea level habitat.)

If the mass penalty, crew productivity penalty, and the potential crew safety impact of an intermediate airlock between the laboratory and habitat modules are acceptable, then a habitat can be designed with differing pressures in the various elements, allowing zero prebreathe EVA from a lower pressure element while also allowing life science experiments at sea-level conditions.

If desirable from an overall systems standpoint, an alternate diluent gas such as neon may reduce EVA oxygen prebreathe time requirements. (Faster tissue washout)

If the habitat design is development cost-driven, then an Earth sea-level atmosphere can reduce development cost. (More off-the-shelf hardware)

If the habitat design is driven by logistics costs, then a reduced pressure atmosphere can reduce logistics costs. (Reduced gas leakage)

If EVA's are expected to be infrequent, then a slightly higher R value may be acceptable than would be for frequent EVA's. (Cumulative probability of decompression sickness over multiple EVA's)

9.0 Glossary

Alveoli: the terminal air sacs in the lungs, in which oxygen absorption takes place

Atelectasis: the collapse of the alveoli

Atmospheric Pressure: the sum of all the partial pressures attributable to the constituents of a gaseous mixture inside a habitat or EMU

Decompression Ratio (also R): the ratio of the sum of the partial pressures of all diluent gases dissolved in body tissues to the atmospheric pressure exerted on the body after a decompression

Decompression Sickness: the state of physiologic dysfunction due to evolution of dissolved gases in the body. Comprised of several symptoms and ill effects, including exhaustion, extremity pain and/or numbness, pulmonary manifestations (e.g. "the chokes"), dysbaric embolism, spinal cord dysfunction, cerebral dysfunction, and vestibular dysfunction. Hyperbaric therapy is the treatment of choice for decompression sickness and related disorders.

Diluent : an inert gas used to lower the concentration of oxygen in an atmosphere and/or to increase the atmospheric pressure

Extravehicular Mobility Unit (also EMU): the integrated element consisting of portable life support subsystem and space suit subsystem which enables crew extravehicular activity

Habitat: any element or collection of elements having an internal atmosphere with the capability to support the lives of human crewmembers or food crops, but specifically excluding the single-person EMU

Hematocrit: red blood cell volume fraction in relation to whole blood

Hypoxia: a state of insufficient oxygen in body tissues to maintain normal physiologic function. Symptoms can include impaired night vision, impaired judgment, and unconsciousness.

Oxygen Concentration (also Percent Oxygen): the volume percent of oxygen in a mixed atmosphere

Oxygen Pressure (also Oxygen Partial Pressure): the absolute pressure caused by the oxygen content of a mixed atmosphere

Oxygen Toxicity: harmful effects of breathing an atmosphere with the partial pressure of oxygen greater than normal. Pulmonary oxygen toxicity, a type of chemical burn of lung tissues, is caused by exposure to high partial pressure of oxygen for a period of time, i.e. partial pressure of oxygen greater than approximately 40.5 kPa (5.9 psia) for more than approximately 24 hours. Symptoms can include chest pain, dry cough, and fulminant pulmonary edema.

Partial Pressure: the pressure attributable to one constituent of a gaseous mixture

R: see Decompression Ratio

10.0 References

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