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Bounding the Spacecraft Atmosphere Design Space for Future Exploration Missions

Kevin E. Lange, Alan T. Perka, Bruce E. Duffield and Frank F. Jeng
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Houston, Texas

June 2005

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Table of Contents

Tables

Figures

1 Introduction

> *In the selection of ideal space cabin atmospheres there has arisen a fascinating interaction between human physiology, the gaseous environment, the machine, and the mission. The systems approach, which has been so successful in aiding the selection of ideal hardware, must be brought to bear once again.* [Roth (1964)]

The selection of spacecraft and space suit atmospheres for future human space exploration missions will play an important, if not critical, role in the ultimate safety, productivity, and cost of such missions. Internal atmosphere pressure and composition (particularly oxygen concentration) influence many aspects of spacecraft and space suit design, operation, and technology development. Optimal atmosphere solutions must be determined by an iterative process involving research, design, development, testing, and systems analysis. A necessary first step in this process is the establishment of working bounds on the atmosphere design space.

1.1 Historical Spacecraft and Space Suit Atmospheres

> *The manned flights of the United States and Russia have been both successfully accomplished with diametrically opposed philosophies regarding cabin environments. The Russians have chosen for their flights an oxygen-nitrogen environment of essentially the same composition and pressure as air at sea level. With less of a weight problem than the United States has had, their philosophy has been "Better the devil you know than the one you don't." In Project Mercury, simplicity of control engineering and minimization of weight were considerations which led to selection of 100% oxygen at 5 psi as the cabin atmosphere.* [Roth (1964)]

Historical spacecraft cabin and space suit atmospheres are compared in Table 1-1. Also compared are the time and conditions required for prebreathing pure oxygen prior to extravehicular activity (EVA). For the early NASA missions through Apollo, spacecraft operated at a low 34.5 kPa cabin pressure with a 100% oxygen atmosphere. The space suit also operated with a 100% oxygen atmosphere at a lower pressure of 25.8 kPa. Because no inert diluent gas was employed, no prebreathe was required prior to EVA. Skylab introduced a mixed nitrogen/oxygen cabin atmosphere at 70% oxygen. The nitrogen partial pressure for the Skylab missions was not high enough to necessitate a prebreathe for EVA. Although prebreathing was not required for EVA in the early NASA missions, a three-hour oxygen prebreathe was performed prior to launch to prevent decompression sickness on the change from Earth ambient pressure (101.3 kPa) to the on-orbit spacecraft pressure (34.5 kPa) (Nicogossian (1982)). One astronaut later reported that he had experienced decompression sickness symptoms (bends) following launch on each of his two flights (Hawkins (1975)).

More recent NASA spacecraft, as well as Soviet/Russian spacecraft, have used a more Earth-normal cabin atmosphere with a pressure of 101.3 kPa and a nominal oxygen concentration of 21%. The NASA space suit still uses a 100% oxygen atmosphere, but at a somewhat higher pressure of 29.6 kPa. Under these conditions, a pure-oxygen prebreathe of 120-240 minutes is required prior to EVA, depending on the prebreathe protocol. To reduce the prebreathe time, the Space Shuttle is capable of operating at a reduced pressure of 70.3 kPa and an elevated oxygen concentration of nominally 26.5%. Under these conditions, the prebreathe time is reduced to 40 minutes. The Russian Orlan space suit operates at a higher 39.2 kPa pressure, allowing a 30 minute prebreathe from an Earth-normal cabin atmosphere.

Table 1-1. Historical Spacecraft Cabin and Space Suit Atmospheres

Program	Cabin Pressure, kPa (psia)	Cabin Oxygen Concentration, volume %	EVA Suit Pressure, kPa (psia)[a]	EVA Prebreathe Time, min	EVA Prebreathe Conditions
Mercury	34.5 (5)	100	-	-	-
Gemini/Apollo	34.5 (5)	100	25.8 (3.75)	0	-
Skylab	34.5 (5)	70	25.8 (3.75)	0	-
Shuttle	70.3 (10.2)	26.5	29.6 (4.3)	40	In-suit (after 36 hours at 70.3 kPa)
	101.3 (14.7)	21	29.6 (4.3)	240[c]	In-suit
ISS/US	101.3 (14.7)	21	29.6 (4.3)	120-140	Mask and in-suit; staged w/exercise
				240[c]	In-suit
Salyut, Mir, ISS/Russian	101.3 (14.7)	21	40.0 (5.8)[b]	30	In-suit

[a] At 100% oxygen.
[b] Can be reduced to 26.5 kPa (3.8 psia) for short-duration work regime.
[c] Under emergency conditions, a minimum of 150 minutes of unbroken prebreathe is recommended.
References: Carson (1975), McBarron (1993), Waligora (1993), NASA (2002), NASA (2003).

The use of Earth-normal cabin atmospheres has allowed much more extensive use of non-metallic materials and off-the-shelf items than in the early NASA spacecraft. An Earth-normal cabin atmosphere is also generally preferred for life and microgravity science studies to eliminate extra variables in comparison with ground-based studies.

1.2 Atmosphere Selection Drivers

For future exploration missions, there are many issues that drive spacecraft and space suit atmosphere selection. Some of the important issues are listed below.

Crew Health and Safety Requirements

- Crew Physiology
- Decompression Sickness Prevention
- Emergency EVA Capability
- Rapid Cabin Decompression Response
- Radiation Protection

Materials Requirements

- Materials Flammability
- Materials Off-gassing

Science Requirements

- Microgravity and Partial-Gravity Science/Physiology Studies

Preflight Testing Requirements

- Human
- Equipment

Program Requirements

- Mission Segments and Durations

- EVA Frequency
- Cross-Vehicle Atmosphere Compatibility

Mission, Vehicle, and Space Suit Optimization

- Structure, Equipment, and Consumable Mass
- Thermal Control Power Requirements
- Space Suit Mobility and Glove Dexterity
- System Safety and Reliability
- Crew Time
- Crew Comfort and Performance
- Cost

These issues can be broadly categorized as either requirements related or optimization related. In a simplified sense, requirements-related issues can be considered as defining the atmosphere design space, while optimization-related issues govern the ultimate selection of atmosphere conditions within the design space. In reality, optimization-related issues will influence some requirements, so that the overall atmosphere selection process becomes necessarily iterative in nature.

1.3 Atmosphere Selection Process

A flowchart of the envisioned atmosphere selection process is shown in Figure 1-1. As future exploration missions are defined, requirements will flow down that can be used to bound the spacecraft and space suit atmosphere design space. Initially, such requirements may be preliminary in nature, pending necessary research and further mission definition. From within this "working" design space, candidate atmosphere design values can be chosen and used in more detailed analyses and optimization studies involving all affected systems. If necessary, the design space can be refined based on updated requirements.

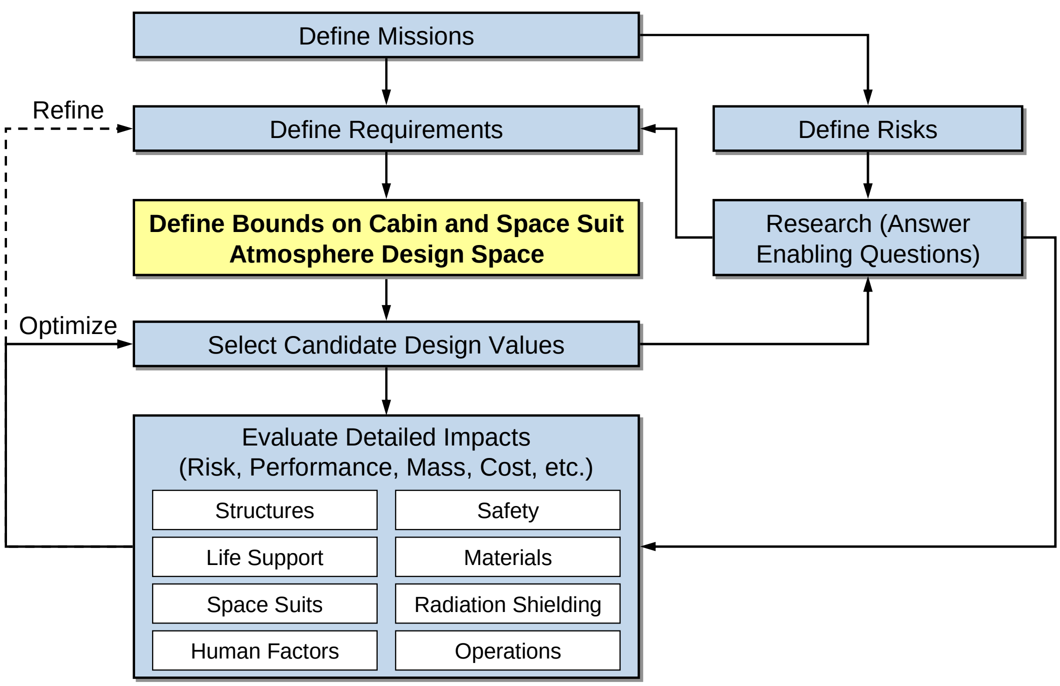

Figure 1-1. Envisioned atmosphere selection process.

1.4 Approach and Assumptions

The approach adopted in the current study was to define working bounds on the spacecraft cabin atmosphere pressure and oxygen concentration design space based on an initial assessment of requirements in three areas:

1. Respiratory Physiology
2. Decompression Sickness Prevention
3. Materials Selection

These areas were chosen because of their high-level importance in crew health and safety, and because it was believed that the resulting bounds would provide the greatest restriction on the design space. The focus on these areas is not intended to ignore or diminish the importance of other issues, but simply to provide a narrowed starting point for further studies.

Definitive requirements related to respiratory physiology, decompression sickness prevention, and materials selection have not been established for future exploration missions. An initial assessment of these requirements was made in this study based on current requirements, input from experts, and the authors' judgment. References and rationale for tentative requirements are provided in this report. A critical review of these tentative requirements should be part of any follow-on activity.

The inclusion of decompression sickness prevention as a bounding issue implies significant extravehicular activities (EVAs). The primary focus of this study was on spacecraft involved in surface exploration missions with a high frequency of EVAs. Expansion of the design space for spacecraft with few EVAs is briefly discussed later in this report.

Throughout this study, the space suit internal atmosphere was assumed to be 100% oxygen. Bounds on the space suit pressure were not specifically addressed. Instead, two candidate space suit pressures were chosen for detailed analysis in the baseline study: the current NASA space suit pressure of 29.6 kPa (4.3 psia) and a higher space suit pressure of 41.4 kPa (6 psia). The latter pressure is slightly higher than the Russian space suit nominal pressure and has been considered in earlier studies. Issues that must be addressed with increasing space suit pressure include a reduction in glove mobility and a resultant increase in EVA crewmember fatigue. For the spacecraft cabin atmosphere, the diluent gas was assumed to be nitrogen, although alternative inert gases or inert gas mixtures could be considered.

The next section describes the baseline atmosphere study performed during the second and third quarters of fiscal year 2004. This study has been presented in its current form in a number of forums (Lange (2004a, 2004b, 2005). Extensions to the baseline study are presented in Section 3.

2 Baseline Study

This section addresses each of the three selected requirement areas in succession. The resulting bounds are then combined to arrive at several plots of the spacecraft atmosphere design space for different values of the space suit pressure and decompression sickness risk parameter (tissue ratio).

2.1 Respiratory Physiology

Current NASA standards (NASA (1995)) define high-level, physiologically-driven requirements for breathable atmospheres:

- Provide sufficient total pressure to prevent vaporization of body fluids (> 6 kPa (0.9 psia)).
- Provide sufficient oxygen partial pressure for adequate respiration, but not so great as to induce oxygen toxicity.

- For long durations (in excess of two weeks), provide a physiologically inert gas to prevent atelectasis.[1]

The impact of the second of these requirements on the atmosphere design space is shown in Figure 2-1. For different combinations of atmosphere total pressure and oxygen concentration, a region of unimpaired performance exists that is bounded by regions of hypoxia (oxygen deficiency) and oxygen toxicity.

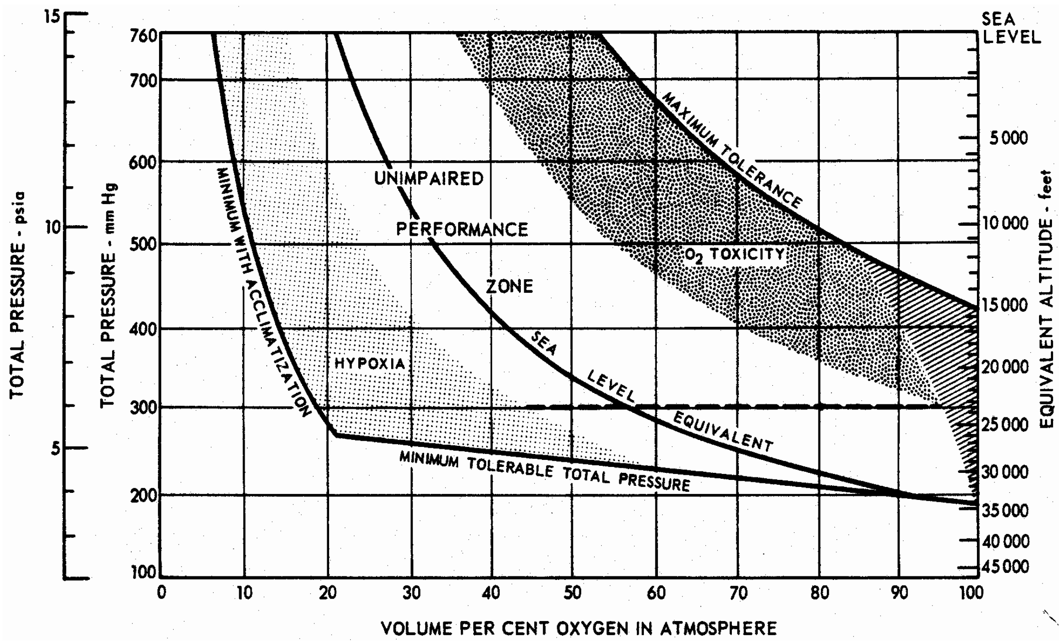

Figure 2-1. Physiological response to atmospheres of different total pressure and oxygen concentration (from Webb (1964); also NASA (1995)).

The sea-level equivalent (or normoxic) curve in Figure 2-1 defines atmosphere conditions that provide the same oxygen partial pressure within the alveoli of the lung (the site of oxygen transport to the blood) as exists for a normal sea-level atmosphere. The alveolar oxygen partial pressure is a critical determinant of physiological oxygen sufficiency and differs from the atmosphere oxygen partial pressure because of absorption of oxygen and dilution by water vapor and carbon dioxide within the lung. The relation between these two oxygen partial pressures is described by the Alveolar Gas Equation. A generalized version of this equation that accounts for carbon dioxide in the inspired air is derived in Section 6.

Figure 2-2 shows three pairs of curves generated using the Alveolar Gas Equation, each corresponding to a different alveolar oxygen partial pressure. Each pair includes a solid curve generated assuming "textbook" values for the inspired carbon dioxide partial pressure and respiratory quotient (see Section 6), and a dashed curve generated using values typically assumed in spacecraft life support analysis. An equivalent altitude can be associated with each alveolar oxygen partial pressure as shown in Table 2-1. This table also contains the values assumed for other parameters.[2]

---

[1] Absorption atelectasis is the collapse of obstructed alveoli due to complete gas absorption (see West (1990)).

[2] An inspired-air water partial pressure, p_{IH2O}, of 9.2 mm Hg was assumed for all analyses in this report.

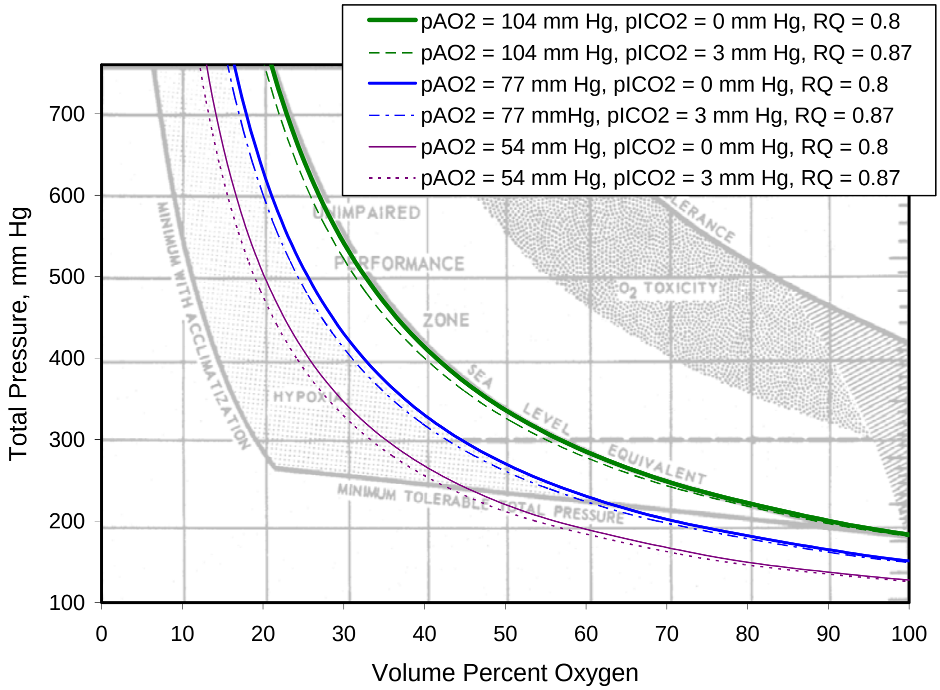

Figure 2-2. Curves of constant alveolar oxygen partial pressure corresponding to three equivalent altitudes. Results are shown for both "textbook" conditions and typically assumed spacecraft conditions (see Table 2-1).

Table 2-1. Respiratory Parameters Assumed in Baseline Study

Equivalent Altitude		p_{AO2}	p_{ACO2}	p_{AH2O}	***RQ***
m	**ft**	**mm Hg**	**mm Hg**	**mm Hg**	
0	0	104	40	47	0.8 or 0.87
1829	6000	77	34	47	0.8 or 0.87
3658	12000	54	32	47	0.8 or 0.87

p_{AO2} = alveolar oxygen partial pressure
p_{ACO2} = alveolar carbon dioxide partial pressure
p_{AH2O} = alveolar water partial pressure
RQ = respiratory quotient (respiratory exchange ratio)

A comparison between the corresponding solid and dashed curves shows a small effect of parameter assumptions that can probably be neglected at this level of analysis. A comparison between the solid curves and the underlying reproduction of Figure 2-1 shows good agreement between the sea-level equivalent curves. Good agreement is also shown between the 1829-m (6000-ft) equivalent curve and the boundary between the unimpaired performance zone and the hypoxic zone. The corresponding alveolar oxygen partial pressure of 77 mm Hg (1829-m equivalent) is reported by Waligora (1991, 1993) to be the minimum partial pressure for which "acclimation can be nearly complete."

2.1.1 Respiration-Related Bounds

Based on these results, the normoxic (sea-level equivalent) curve and the hypoxic boundary (1829-m equivalent) curve generated using textbook parameter values were assumed as bounds on the atmosphere design space.[3] These curves are reproduced in Figure 2-3. Also shown in this figure for comparison are historical spacecraft atmosphere designs. Possible impacts of reduced gravity on human acclimation to sub-normoxic atmospheres should be considered in future refinements of the hypoxic boundary.

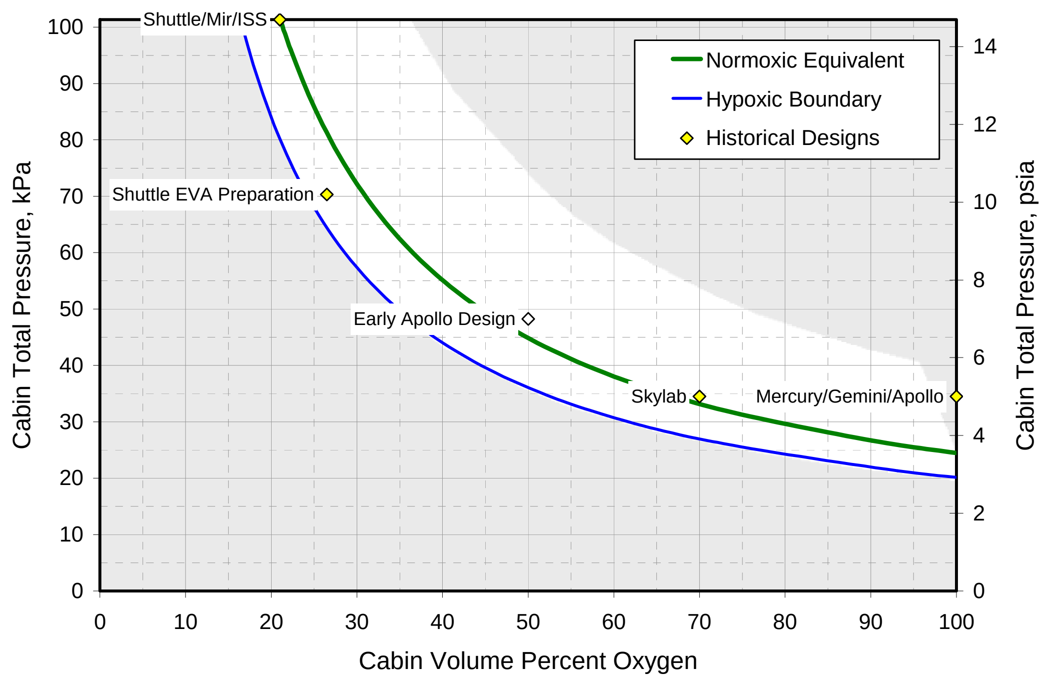

Figure 2-3. Assumed design bounds based on respiration requirements. Historical spacecraft cabin atmosphere conditions are shown for comparison.

2.2 Decompression Sickness Prevention

Decompression sickness takes place when the inert gas (generally nitrogen) that normally is dissolved in body tissues at one pressure forms a gas phase ("bubbles") at a lower ambient pressure, when the tissues become supersaturated with nitrogen. [Powell (1993)]

Decompression sickness (DCS) is an important consideration for mixed cabin atmospheres when EVAs are performed in lower-pressure space suits, and when changes in cabin pressure can occur as a result of planned activities and emergencies. DCS is a potentially debilitating and life-threatening condition. Symptoms can include pain ("the bends"), pulmonary manifestations ("the chokes"), skin manifestations, circulatory collapse, and neurological disorders (NASA (1995)). A common approach for preventing or minimizing DCS is to prebreathe pure oxygen prior to depressurization to wash out nitrogen from body tissues.

The occurrence and severity of DCS has been found to correlate to a limited degree with the ratio of the final partial pressure of inert gas in equilibrium with body tissue to the final ambient total pressure. This ratio, R (or TR), is known as the tissue ratio or bends ratio. When the inert gas is nitrogen and the final ambient pressure is the space suit pressure, R can be expressed as follows:

[3] Higher than normoxic oxygen concentrations could be included in the design space but were not included because the higher oxygen concentration would increase flammability, while being physiologically unnecessary.

$$R = \frac{p_{\text{N2-Tissue}}}{P_{\text{Suit}}} \quad (2\text{-}1)$$

The incidence of DCS (as well as venous gas emboli) increases with increasing *R* (see, for example, Horrigan (1993)). In addition to the dependence on *R*, DCS has been found to depend on the duration at reduced pressure, and the degree of physical activity and ambulation at reduced pressure (Conkin (1996, 2001b)). Test data also suggest that at the same *R*-value, a higher space suit pressure will result in a lower probability of DCS (Conkin (1996)).

During a pure-oxygen prebreathe, the elimination of nitrogen from body tissue follows an exponential decay curve with a tissue-dependent half-time, $t_{1/2}$, related to the blood perfusion rate, inert gas diffusion rate, and inert gas solubility in the tissue (Conkin (1987)):

$$p_{\text{N2-Tissue}}(t) = p_{\text{N2-Tissue}}(0)\exp\left[-(\ln 2)\frac{t}{t_{1/2}}\right] \quad (2\text{-}2)$$

In terms of *R* value,

$$R(t) = R(0)\exp\left[-(\ln 2)\frac{t}{t_{1/2}}\right] \quad (2\text{-}3)$$

The initial nitrogen partial pressure in equilibrium with body tissue prior to prebreathing is most appropriately assumed equal to the alveolar nitrogen partial pressure, p_{AN2}, that exists under the spacecraft cabin atmosphere conditions. In correlating the incidence of DCS against *R*, Conkin and coworkers (1987) have used the atmosphere nitrogen partial pressure instead of p_{AN2} to avoid the added complexity of using the Alveolar Gas Equation for intermediate exposures. These authors have also used a theoretical tissue type with a 360-minute half-time for modeling the dependence of DCS incidence on *R*.

For any given spacecraft cabin atmosphere and space suit pressure, Equation 2-3 can be used to calculate the prebreathe time necessary to achieve a final required *R*-value prior to EVA. In establishing a bound on the atmosphere design space based on DCS prevention, the final required *R*-value and the maximum allowable prebreathe time must be established.

2.2.1 Final R-Value

Current NASA prebreathe protocols for the Space Shuttle and International Space Station (ISS) are based on a final *R*-value of 1.65-1.68 after oxygen prebreathe (see Horrigan (1993) and NASA (2002, 2003)). Actual operational values are frequently lower. For surface-exploration EVAs, DCS risks from mixed cabin atmospheres have not been established, nor has the acceptable level of DCS risk. Higher physical loads imposed by ambulation in partial gravity suggest higher DCS risk than in microgravity. DCS symptoms must also be treated locally without the option for a quick return to Earth. A final *R*-value of 1.3-1.4 (following prebreathe) has been suggested by Conkin (2004) as a reasonable range based on current knowledge.

2.2.2 Maximum Prebreathe Time

Minimization of the prebreathe time is highly desirable in missions with frequent EVAs to maximize crew productivity. A prebreathe period of approximately 20 minutes is expected to be available due to the normal time required for space suit purge and checkout procedures. A longer minimum prebreathe (up to 1 hour) may be required to denitrogenate the brain and spinal cord to guard against serious (Type

II) DCS symptoms (Gernhardt (2004)). A prebreathe time of 1 hour is therefore assumed as a tentative upper bound for surface exploration EVAs.

2.2.3 Prebreathe Bound

Equation 2-3 was used to map curves of constant prebreathe time over the spacecraft cabin atmosphere pressure and oxygen concentration design space. Results are shown in Figures 2-4 through 2-7 for space suit pressures of 29.6 kPa (4.3 psia) and 41.4 kPa (6 psia), and for final *R*-values of 1.3 and 1.4. These results were calculated taking $p_{N2\text{-}Tissue}(0)$ equal to the cabin atmosphere nitrogen partial pressure, and using a tissue half-time of 360 minutes. Curves are shown for prebreathe times ranging from 0 minutes to 240 minutes. The 60-minute prebreathe curve (shown dashed and bolded) represents the assumed upper bound on prebreathe time. The strong dependence on space suit pressure is evident by comparing Figures 2-4 and 2-5 with Figures 2-6 and 2-7.

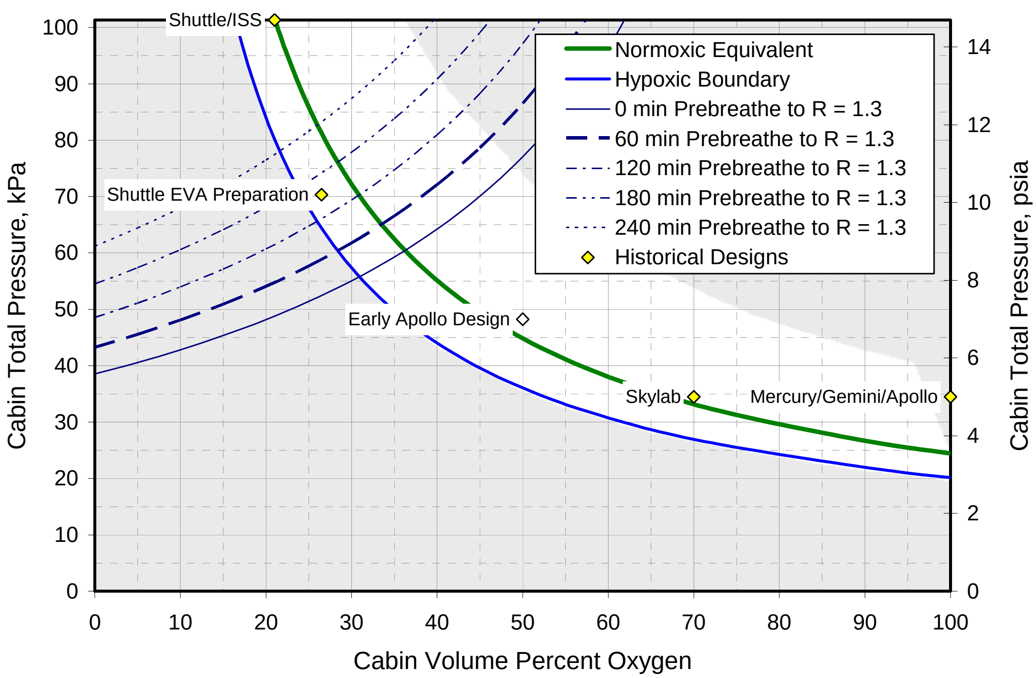

Figure 2-4. Curves of constant EVA prebreathe time for a 29.6 kPa space suit with a final *R*-value of 1.3. Assumed upper bound on prebreathe time is 60 minutes.

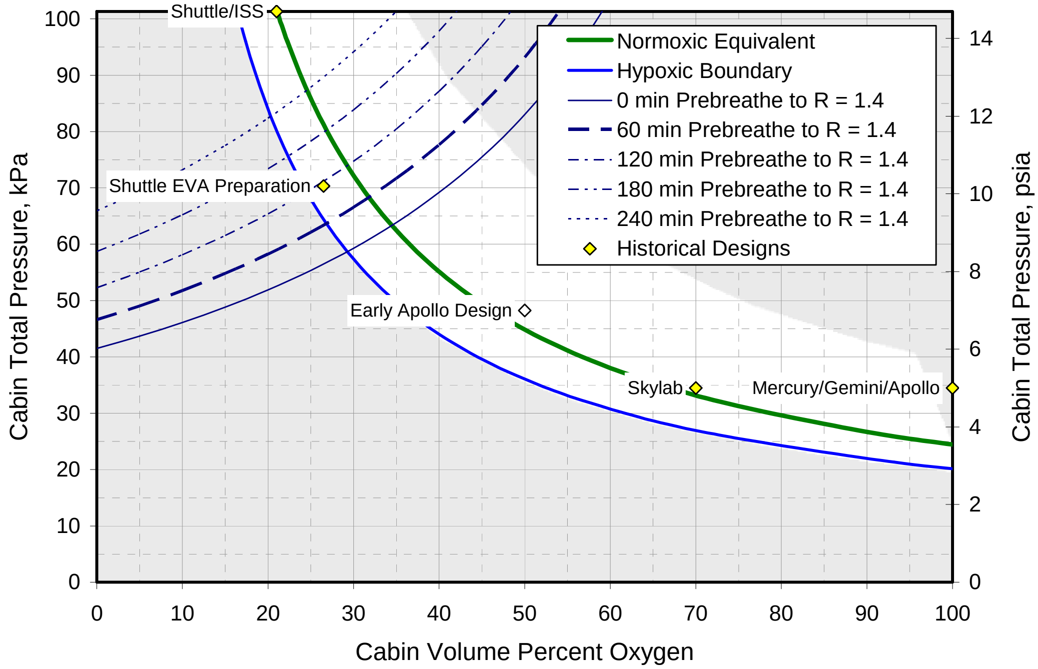

Figure 2-5. Curves of constant EVA prebreathe time for a 29.6 kPa space suit with a final *R*-value of 1.4. Assumed upper bound on prebreathe time is 60 minutes.

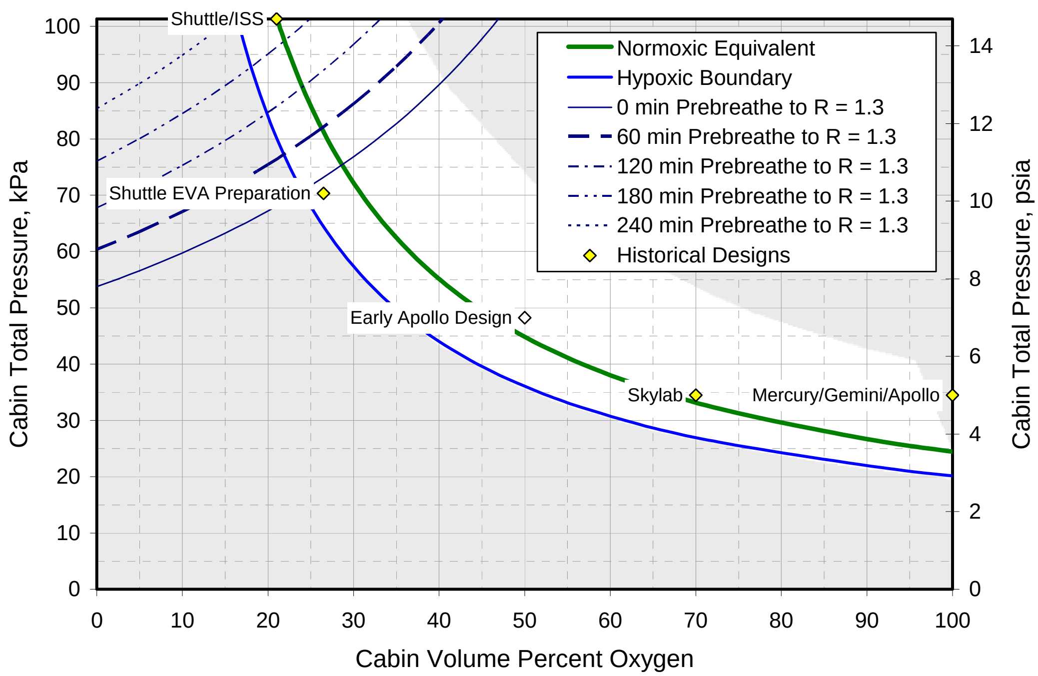

Figure 2-6. Curves of constant EVA prebreathe time for a 41.4 kPa space suit with a final *R*-value of 1.3. Assumed upper bound on prebreathe time is 60 minutes.

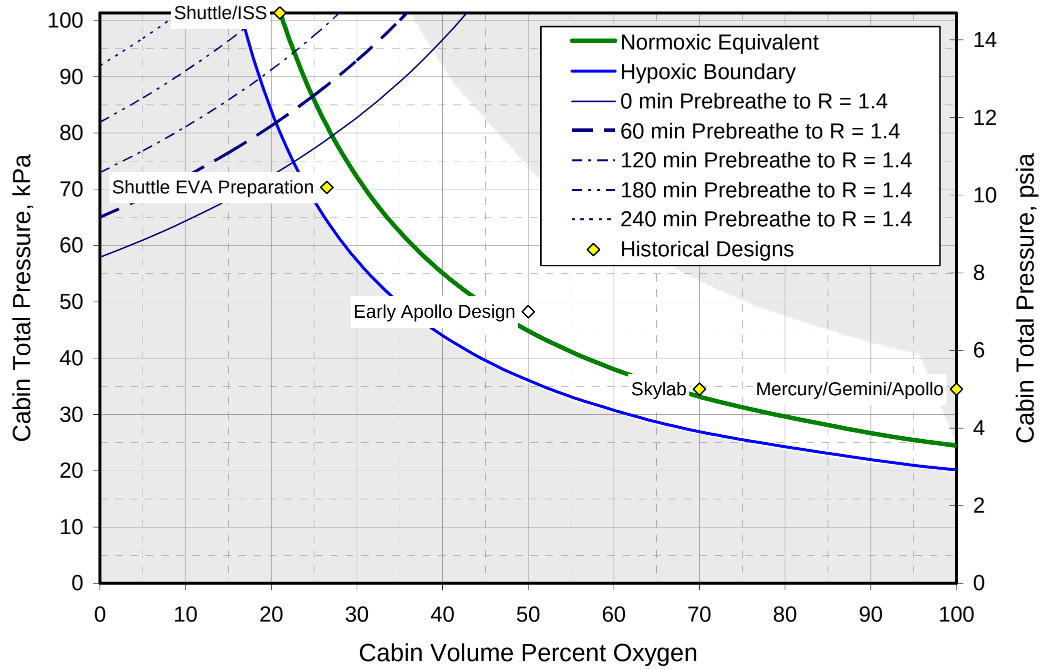

Figure 2-7. Curves of constant EVA prebreathe time for a 41.4 kPa space suit with a final *R*-value of 1.4. Assumed upper bound on prebreathe time is 60 minutes.

2.3 Materials Selection

The selection of materials for use within spacecraft is driven by safety, performance, mass, and cost. Flammability and offgassing are foremost among safety considerations. The flammability of a material is directly affected by spacecraft cabin atmosphere selection. Usage restrictions imposed by flammability requirements can have cascading impacts in areas such as crew radiation protection, structures, and mission operations.

2.3.1 Flammability

> *Spacecraft fire control is based on minimizing potential ignition sources and "eliminating materials that can propagate fire" — This means controlling quantity and configuration of flammable materials to eliminate potential fire propagation paths and ensure any fire would be small, localized, isolated and would self-extinguish without harm to the crew.* [Griffin (2001)]

> *In the closed environment of a spacecraft or extraterrestrial base, with no avenue for escape, a fire is greatly to be feared. Yet, the experience in human-crew space missions to date has been exemplary. … The long-duration exposure in flight and on surface bases in extraterrestrial missions will provide greater opportunities for fire risks, with possible occurrences of mechanical and electrical breakdowns, sensor and alarm-system failures, suppressant leakage, material aging, and human errors. Furthermore, the long missions require a greater level of housekeeping and support activities, which add fire dangers in cooking, laundry, and trash accumulation.* [Friedman (1998)]

By contrast with human respiration that depends primarily on oxygen partial pressure in the atmosphere, materials flammability depends strongly on oxygen concentration (volume percent) and to a lesser extent on total pressure. Increasing oxygen concentration at constant atmosphere pressure decreases the minimum ignition energy, increases the flame spread rate, and increases the amount of extinguishant required to put out a fire (NFPA (2004), Beeson (1997)).

Flight hardware on U.S. spacecraft must comply with NASA-STD-6001, "Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion" (NASA (1998)). For nonmetallic solids, the primary flammability test is Test 1, Upward Flame Propagation. This test evaluates whether a material is self-extinguishing under expected worst-case-usage conditions of pressure, temperature, oxygen concentration, and thickness. A 12-in.-long (30-cm-long) sample of the material is mounted vertically in a test chamber and ignited chemically at the bottom in a quiescent atmosphere environment. A material passes if for at least three samples the vertical burn length for all samples is less than 6 in. (15 cm) and the material does not propagate a flame by generating burning debris sufficient to ignite a sheet of paper mounted 8 in. (20 cm) below the sample holder. For materials that fail Test 1 and that remain candidates for use, NASA-STD-6001 requires a system flammability evaluation. In general, flammable materials of limited size and quantity can be used by isolating the articles from ignition sources and by eliminating or restricting fire propagation paths (Friedman (1999), Griffin (2001)). Approaches include enclosing flammable articles in nonflammable containers and covering them with nonflammable materials or coatings.

Although NASA-STD-6001 Test 1 is performed with an initially quiescent surrounding atmosphere, the strong buoyancy-induced gas flow that occurs in Earth-normal gravity assists upward flame propagation by supplying oxygen to the flame zone, removing combustion products, and heating the unburned sample. Results of this test have been generally considered conservative for assessing material flammability in microgravity, although the degree of conservatism is dependent on the material and on the degree of forced ventilation flow ((Friedman (1999), Hirsch (2000)). Studies with thin-paper fuels have shown that both higher flame-spread rates and sustained combustion at lower oxygen concentrations can be obtained at moderate air velocities below that of normal-gravity-induced buoyant flows (Olson (1991), Friedman (1989)). Partial gravity conditions characteristic of the Lunar or Mars surface may therefore in some cases represent a more severe flammability environment than either normal gravity or quiescent microgravity (Friedman (1998)). Additional research in this area is needed.

The pass/fail logic of NASA-STD-6001 Test 1 does not provide a measure of how far a material is removed from combustion threshold conditions and does not allow "a precise quantitative comparison" with other ground or microgravity flammability test results (Hirsch (2001, 2002)). The use of existing Test 1 results for evaluating the flammability limits of materials over a range of atmosphere oxygen concentration is thus limited. Hirsch and Beeson (Hirsch (2001, 2002)) have proposed an extension of Test 1 with a sequential test logic to determine a material's self-extinguishment limits.

A commonly reported measure of flammability limits for polymeric materials is based on ASTM D 2863, Standard Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index) (ASTM (1997)). The oxygen index[4] defined according to ASTM D 2863 is the minimum oxygen concentration that sustains combustion of a vertically supported sample ignited at the top. A countercurrent upward air velocity of approximately 4 cm/s is maintained. The downward flame propagation conditions of this test are generally considered less severe than those of upward flame propagation and not conservative for assessment of microgravity flammability (Friedman (1999)). The European Space Agency (ESA) originally included the oxygen index test as part of its flammability testing requirements (ESA (1992)), but provided an acceptance criterion that the oxygen index be at least 10 percentage points higher than the oxygen concentration in the worst-case atmosphere. More recently, ESA has replaced the oxygen index test with an upward flame propagation test for determining flammability limits based on an RKK/Energia test method (ECSS (1999)).

[4] Also called the limiting oxygen index (LOI) or critical oxygen index.

Figure 2-8 compares literature data for the minimum oxygen concentration to sustain combustion of polymeric materials as a function of the polymer hydrogen content. The significance of polymer hydrogen content will be discussed shortly. The data include standard (downward flame propagation) oxygen index values obtained from handbooks, product literature, and Orndoff (1995), as well as more limited test results for upward flame propagation conditions. The upward flame propagation results were obtained from Ikeda (1983), Hirsch (2001), and Hirsch (2003).[5] Where identifiable from the data source, polymer formulations containing flame retardants or fillers were excluded in order to accurately determine the hydrogen content and to reflect the flammability characteristics of the base material. A horizontal line at 30% oxygen indicates the current NASA maximum testing limit for general material use inside spacecraft habitable (cabin) areas.

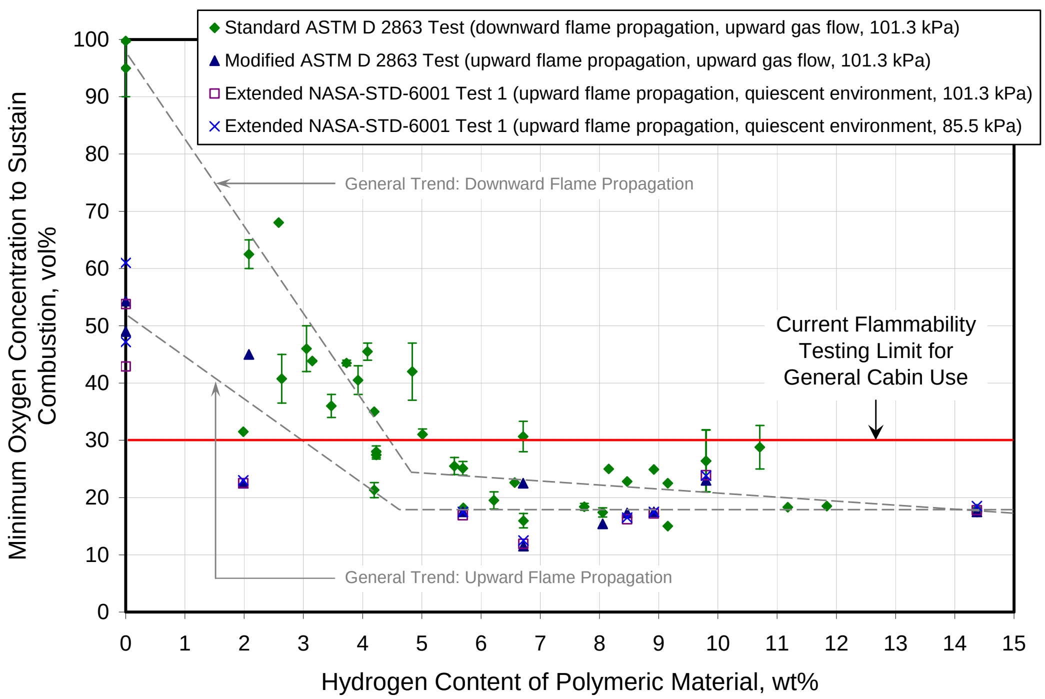

Figure 2-8. Influence of polymer hydrogen content and test conditions on the minimum oxygen concentration to sustain combustion.

The influence of different gas flow and atmosphere pressure conditions in the upward flame propagation tests are shown in Figure 2-8 to be small compared to the influence of flame propagation direction. General trends of the two propagation-direction groups are suggested by the two sets of dashed lines. As discussed above, upward flame propagation is generally more severe and allows combustion to be sustained to lower oxygen concentration. The difference in results between upward flame propagation and downward flame propagation appears to generally increase with decreasing polymer hydrogen content. For polyethylene (14.4 wt% hydrogen), the minimum oxygen concentration to sustain combustion changes by less than 1 percentage point with flame propagation direction, whereas it changes by roughly 50 percentage points for polytetrafluoroethylene (PTFE, 0 wt% hydrogen). A similar trend with polymer heat of combustion may explain this behavior. Hirsch and coworkers (2003) noted that for polymers with a high heat of combustion (e.g., polyethylene) the minimum oxygen concentration to sustain combustion is less influenced by propagation direction or sample preheating than for polymers

[5] Corresponding standard (downward flame propagation) oxygen index values were also determined in these studies. These values were included in the Standard ASTM D 2863 data set.

with a low heat of combustion (e.g., PTFE). They suggested that enhanced heat feedback could have a greater effect on polymers with a lower heat of combustion.

The results in Figure 2-8 indicate that many non-metallic polymeric materials are flammable even at an Earth-normal oxygen concentration of 21% and that the number of available self-extinguishing materials falls off rapidly as the oxygen concentration is increased. Polymeric materials suitable for unrestricted use in substantially enriched oxygen atmospheres are generally very low in hydrogen content.

2.3.2 Radiation Shielding

Research in deep-space ionizing radiation has found that metals are much poorer than hydrogen-containing materials in shielding the crew from high-energy particles associated with Solar Particle Events (SPE) and Galactic Cosmic Radiation (GCR):

> *Aluminum has been found to be a poor shield material when dose equivalent is used with exposure limits for low Earth orbit (LEO) as a guide for shield requirements. Because the radiation issues are cost related—the parasitic shield mass has high launch costs—the use of aluminum as a basic construction material is clearly not cost-effective and alternate materials need to be developed.* [Wilson (1997)]
>
> *Shielding against the radiation environment involves the entire spacecraft, meaning that apparently simple design choices (e.g., aluminum structures as opposed to polymer composites) can have adverse effects on radiation exposures. Shielding during every aspect of the mission is necessary to ensure crew safety, health, and performance.* [Allen (2003)]

The above statements emphasize that crew radiation protection is affected by materials selection throughout the spacecraft. Stored hydrogen (H_2) and hydrogen-containing materials, such as water and organic polymers, have been considered for use in optimizing spacecraft radiation shielding effectiveness. Polymers and polymer composites offer the potential of providing both structural and shielding functions at reduced mass compared to metals. Research is being conducted on the development of multifunctional structural elements containing high concentrations of polyolefins, such as polyethylene (Wilson (2003, 2004)). The use of polymer composite materials to reduce structural mass has been previously assumed in some NASA exploration mission design studies (Drake (1998)).

2.3.3 Mission Operations

Longer mission duration drives reuse and recycling of materials in order to reduce consumable and expendable supplies that must be launched and wastes that must be stored. As noted earlier in the quote from Friedman (1998), long missions will require greater housekeeping and support activities, including cooking, laundry, and trash management. Regular maintenance operations on equipment and spacesuits, such as cleaning and part replacement, will be necessary. The capability for local part fabrication may also be required.

With increasing mission duration, advanced life support systems will be driven to higher closure of the human support loop by including food production and waste recycling systems. Even for nearer-term missions, drying processes are being considered to recover water from solid wastes, and high-temperature processes are being considered to decompose wastes for microbial stabilization and volume reduction. These operations will inevitably involve increased handling and processing of materials that could include potentially flammable items such as clothing, towels, food packaging, plant biomass, paper, and used filters.[6]

[6] Cellulose, a primary constituent of cotton and paper, has a hydrogen content of 6.2 wt% and a reported oxygen index of 18-21% without added flame retardants.

2.3.4 Materials Bound

For longer duration space missions outside of Earth orbit, material usage is expected to differ from current practice by increased use of polymeric materials to optimize radiation shielding and reduce structural mass, and by increased handling and processing of consumable and expendable items for reuse, resource recovery, stabilization, or volume reduction. Based on the flammability results in Figure 2-8, these considerations would suggest a cabin oxygen concentration of Earth-normal (21%) or lower. Indeed, oxygen concentrations below Earth-normal have been proposed to reduce flammability hazards (Shvartz (1990)). The use of flame retardants, fillers, nonflammable coatings, and other configuration controls will extend the usage range of polymeric materials containing significant hydrogen content, but it seems unlikely to the authors that this will exceed the current 30% oxygen limit. A tentative upper bound on spacecraft cabin oxygen concentration of 30% is assumed based on the above considerations and the extensive experience in materials selection and fire prevention at this condition from the Space Shuttle Program.

2.4 Resultant Design Space

The resultant design space obtained by imposing the proposed respiratory-related, prebreathe, and materials bounds is shown in Figures 2-9 through 2-12 for the two space suit pressures and two final *R*-values. The results show a very small design space for the 29.6 kPa (4.3 psia) space suit pressure, with an expanded design space for the 41.4 kPa (6 psia) space suit pressure. The Earth-normal cabin atmosphere currently used on the Space Shuttle and ISS is not included in any of the design spaces.

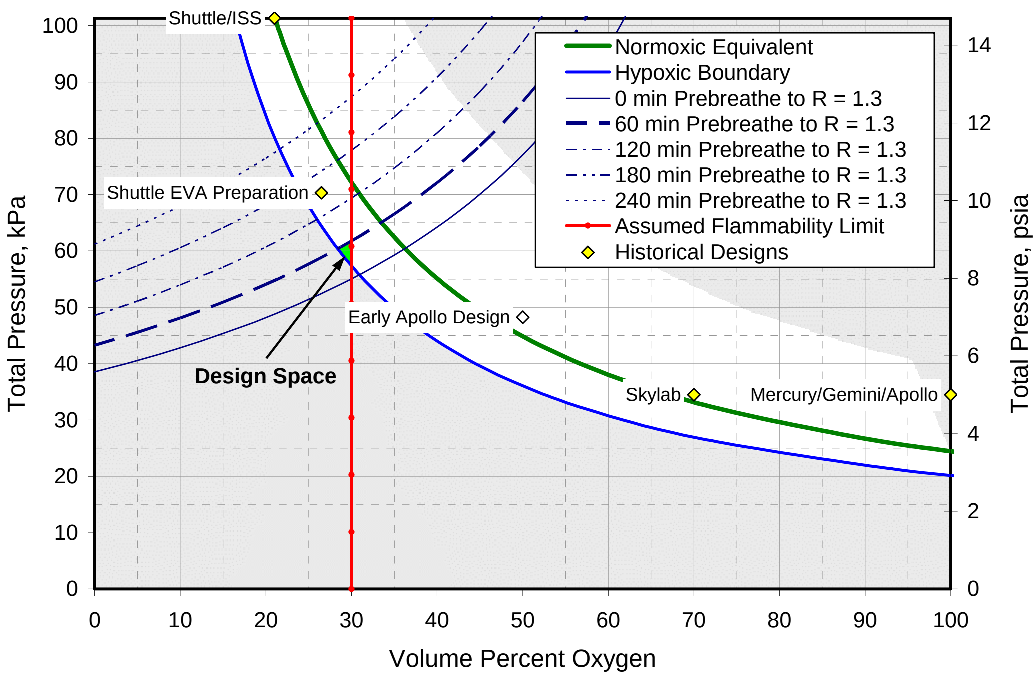

Figure 2-9. Resultant spacecraft cabin atmosphere design space for a 29.6 kPa space suit with a final EVA prebreathe *R*-value of 1.3.

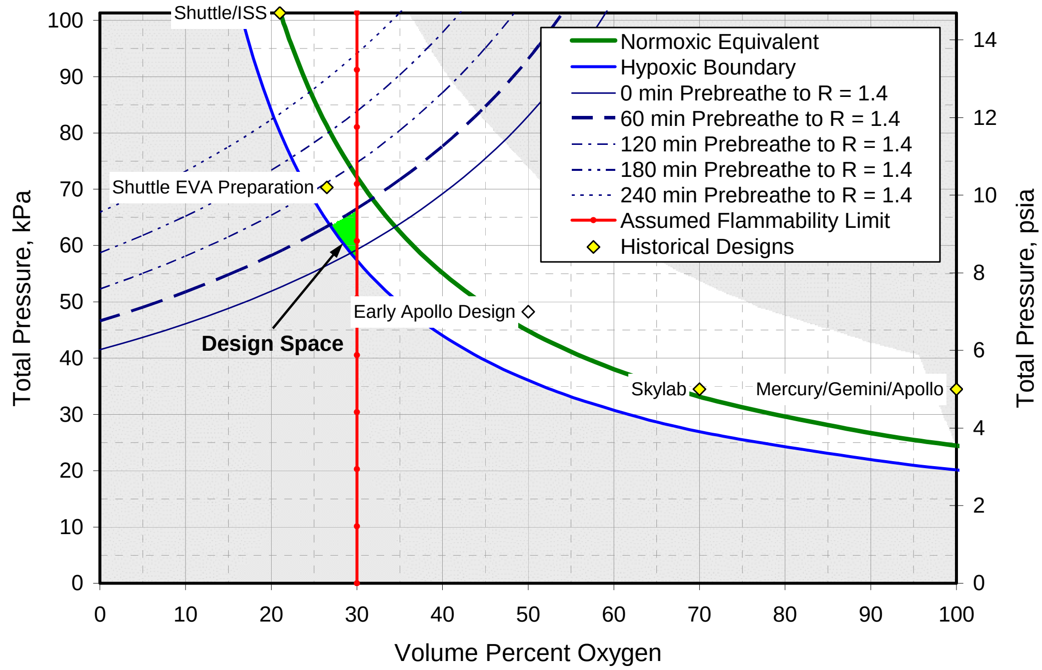

Figure 2-10. Resultant spacecraft cabin atmosphere design space for a 29.6 kPa space suit with a final EVA prebreathe *R*-value of 1.4.

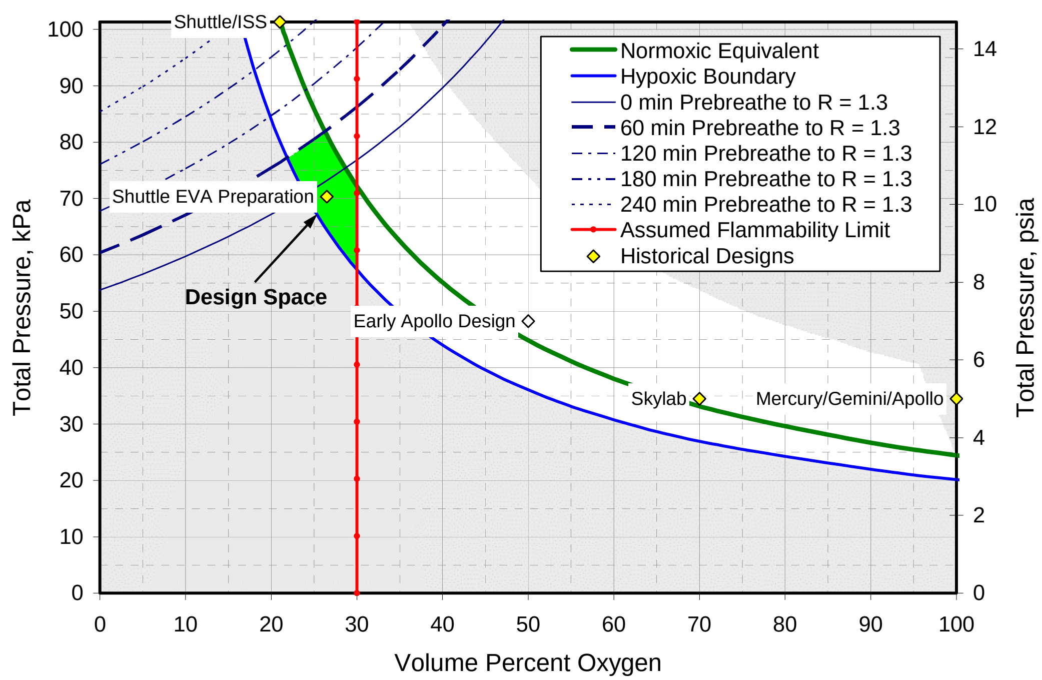

Figure 2-11. Resultant spacecraft cabin atmosphere design space for a 41.4 kPa space suit with a final EVA prebreathe *R*-value of 1.3.

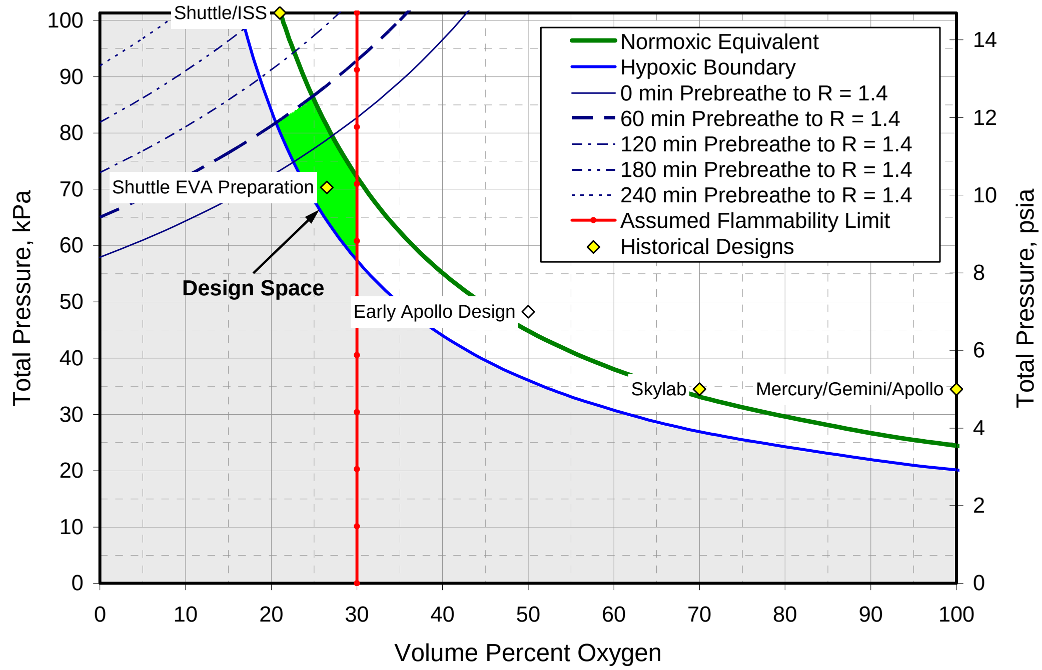

Figure 2-12. Resultant spacecraft cabin atmosphere design space for a 41.4 kPa space suit with a final EVA prebreathe *R*-value of 1.4.

2.5 Summarized Results and Conclusions from the Baseline Study

The baseline study has defined narrowed cabin atmosphere design spaces that can be used as starting points for more detailed studies. For the current 29.6 kPa (4.3 psia) space suit pressure, a small cabin atmosphere design space is found that exceeds the Space Shuttle pre-EVA nominal oxygen concentration of 26.5% and may require recertification of materials above 30% depending on control ranges. A lower cabin oxygen concentration can be achieved by one or more of the following approaches:

- Increasing the space suit pressure.
- Accepting a higher final *R*-value and the associated DCS risk.
- Accepting a longer prebreathe time.
- Allowing a more hypoxic atmosphere.

Any increase in space suit pressure must consider impacts on space suit mass and mobility.

For the higher 41.4 kPa (6 psia) space suit pressure, an expanded design space is found that includes atmosphere oxygen concentrations near 21%, but at lower than sea-level pressures. Such atmospheres would have higher-altitude analogs on Earth that might facilitate spacecraft development and certification testing.

For transit vehicles with few EVAs, a longer prebreathe time may be acceptable that would allow expansion of the design space to include an Earth-normal atmosphere. This would include vehicles that dock with the International Space Station, where inclusion of the Earth-normal ISS atmosphere in the design space will likely be required to avoid airlock operations during crew transfer. Changes in exploration mission design philosophy that would require a much lower frequency of surface EVAs, perhaps in conjunction with greater robotic capabilities, might also allow a longer prebreathe time.

Research is needed to fully define requirements and to assess detailed impacts of cabin and space suit atmosphere selection. The impacts of other atmosphere constituents, such as carbon dioxide and trace contaminants, should also be considered.

3 Extensions to the Baseline Study

This section presents several extensions to the baseline study. These extensions address sensitivity of the results to assumptions and suggest areas where the design space may be expanded or better defined. The topics discussed are also candidates for additional research.

3.1 Alternative Respiratory Parameters

Following completion of the baseline study, a reference was found (Pickard (2002)) that provides alternative respiratory parameters for a range of equivalent altitudes. In particular, Pickard reports higher values than previously assumed for the alveolar carbon dioxide partial pressure at higher altitudes, and reports values of the respiratory quotient that increase with altitude. These parameters are shown in Table 3-1. Using Pickard's parameters, curves of constant alveolar oxygen partial pressure were generated for the same three equivalent altitudes as in Figure 2-2. The results are shown in Figure 3-1.

Table 3-1. Respiratory Parameters from Pickard (2002)

Equivalent Altitude m	Equivalent Altitude ft	p_{AO2} mm Hg	p_{ACO2} mm Hg	p_{AH2O} mm Hg	*RQ*
0	0	103	40	47	0.85
1829	6000	76.8	37	47	0.87
2438	8000	68.9	36	47	0.87
3658	12000	54.3	33.8	47	0.9

A comparison with Figure 2-2 shows that, using Pickard's values, the normoxic curve is slightly lower at moderately elevated oxygen concentrations, whereas there is little net effect on the hypoxic boundary. These differences do not significantly affect the conclusions from the baseline study.

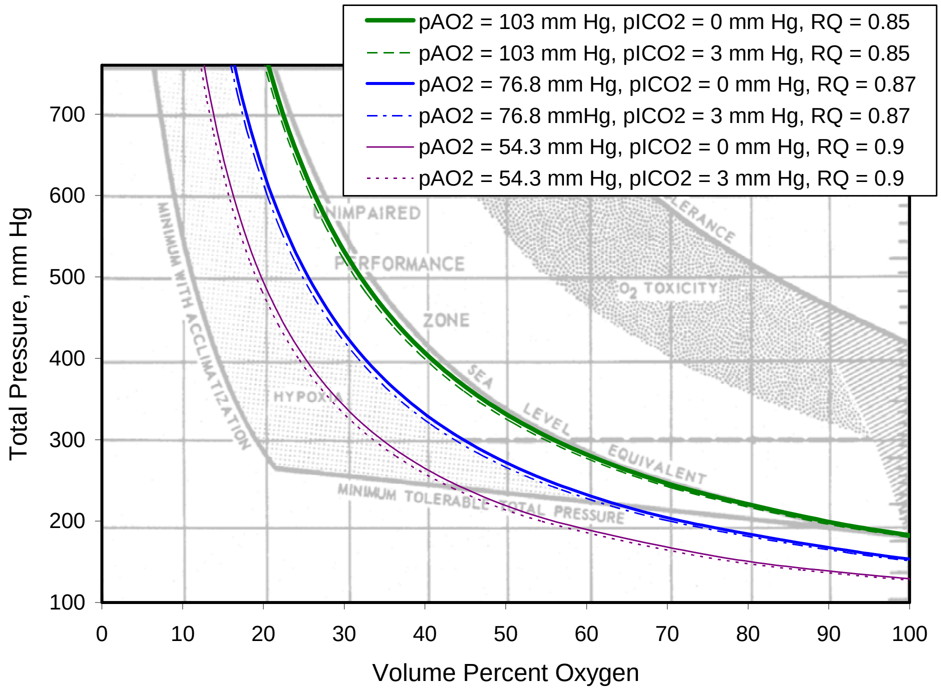

Figure 3-1. Curves of constant alveolar oxygen partial pressure using respiratory parameters from Pickard (2002) (see Table 3-1).

3.2 Lowering the Hypoxic Bound

The alveolar oxygen partial pressure assumed for the hypoxic boundary is based on the limit for nearly complete acclimation reported by Waligora (1991, 1993) and appears to agree with the graphical boundary of the unimpaired performance zone shown in Figure 2-1. This partial pressure is equivalent to that which exists at an altitude of 1829 m (6000 ft). Nevertheless, approximately 130 million people (2.3 % of the Earth's population) live at altitudes of 2000-2500 m (6560-8200 ft) (Cohen (1998)). An indication that higher equivalent altitudes are acceptable in spacecraft, at least for short durations, is also reflected by a recent Space Shuttle flight rule update (NASA (2004)) that directs the crew not to don QDM (Quick Don Mask) during unplanned pressure reduction if breathing air equivalent to a 2438-m (8000-ft) altitude can be maintained.

The impact of lowering the hypoxic bound to a 2438-m (8000-ft) equivalent altitude is shown in Figure 3-2 for a 29.6 kPa (4.3 psia) space suit with a final *R*-value of 1.4. The alveolar oxygen isopleths were generated using the parameters in Table 3-1. An extended design space is obtained that includes somewhat lower oxygen concentrations and total pressures.[7] Although this extension is not large, the lower oxygen concentrations may allow an upper control bound of 30% oxygen or less and thus allow use of Shuttle-certified materials. Even if the 2438-m equivalent alveolar oxygen partial pressure is not considered for nominal conditions, it may be considered in defining the atmosphere control range.

[7] The minimum oxygen concentration is about 1.7 % lower (absolute) than with the 1829-m (6000-ft) equivalent hypoxic bound.

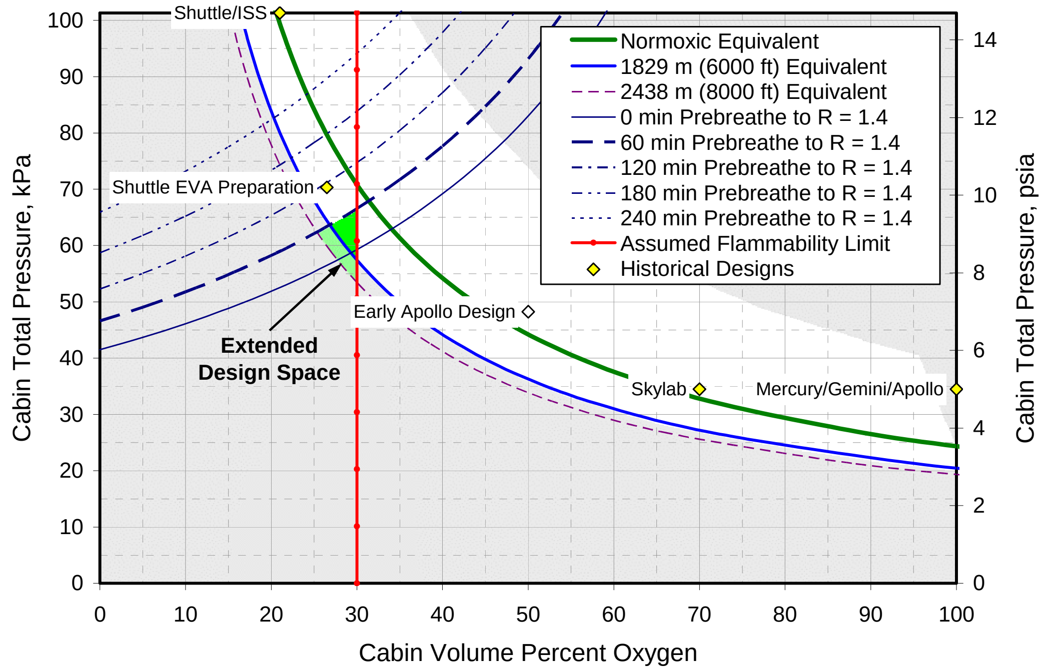

Figure 3-2. Extended spacecraft cabin atmosphere design space with a 2438-m (8000-ft) equivalent hypoxic bound for a 29.6 kPa space suit with a final EVA prebreathe *R*-value of 1.4.

3.3 An Iso-Risk Approach to Prebreathe Bounds for Different Space Suit Pressures

It was noted in Section 2.2 that for the same *R* value a higher final pressure (space-suit pressure) results in a lower probability of DCS according to test data. The baseline-study comparisons between 29.6 kPa and 41.4 kPa space suits at comparable *R* values are therefore not expected to represent comparable DCS risk. In this section, a statistical model of Conkin and coworkers (Conkin (1996)) is used to compare 60 minute prebreathe bounds and the resultant design space for different space suit pressures at the same calculated DCS risk, and to investigate how the design space expands or contracts as the acceptable risk level increases or decreases. A second statistical model (Conkin (2001a)) is used to investigate the influence of prebreathe time on the probability of serious (Type II) DCS. These models were derived from ground-based (1-g) tests that considered, among other variables, the influence of the time of exposure to reduced pressure and the presence or absence of exercise during exposure to reduced pressure.

Table 3-2 compares the probability of DCS, P(DCS), calculated from the model of Conkin and coworkers for the space-suit and *R*-value conditions considered in the baseline study. At comparable *R* value, the model predicts lower DCS risk for the higher space-suit pressure. Similar risk levels (P(DCS) ~ 0.05) are predicted for the 29.6 kPa space suit with an *R* value of 1.3 and the 41.4 kPa space suit with an *R* value of 1.4. *R* values for other levels of DCS risk can be determined from the graphs in Figure 3-3. These graphs include predictions for the 29.6 kPa and 41.4 kPa space suits, as well as the Apollo-era 25.9 kPa space suit. The predictions are based on 4 hours of exposure to reduced pressure (4 hr EVA) with exercise. The highest P(DCS) considered in the baseline study is 0.089 (8.9%), and corresponds to the 29.6 kPa space suit with an *R* value of 1.4. The increase in allowable *R* value with increase in space suit pressure is also supported by biophysical bubble growth models (Conkin (1996), Gernhardt (1991)).

Table 3-2. Calculated DCS Risk for Baseline-Study Cases

EVA Suit Pressure, kPa (psia)	*R*(360)[a]	P(DCS)[b]
29.6 (4.3)	1.30	0.050
29.6 (4.3)	1.40	0.089
41.4 (6.0)	1.30	0.025
41.4 (6.0)	1.40	0.049

[a]*R* value for a tissue compartment with a 360 minute half-time for nitrogen elimination.
[b]Based on a 4 hr EVA with exercise.

In assessing the acceptable level of DCS risk for surface exploration EVAs, it is relevant to consider the predicted and actual incidence of DCS for microgravity EVAs from mixed cabin atmospheres using the 29.6 kPa (4.3 psia) Shuttle EMU space suit and the 40.0 kPa (5.8 psia) Russian Orlan space suit. Figure 3-4 indicates the general ranges of P(DCS) predicted using the statistical model for typical "as-flown" *R* values with the Shuttle and Orlan space suits (*R* = 1.59 and 1.85, respectively). These ranges are bounded by model predictions assuming either exercise or no exercise during the EVA. The statistical model predicts a high incidence of DCS: 16-33% for the Shuttle suit and 27-49% for the Orlan suit. Shirt-sleeve ground testing of the specific as-designed Shuttle and Orlan prebreathe protocols (*R* = 1.65 and 1.89, respectively) results in a similar DCS incidence of 20-25%, whereas no case of DCS has been reported with either suit in microgravity EVAs on-orbit (Conkin (2001c)).

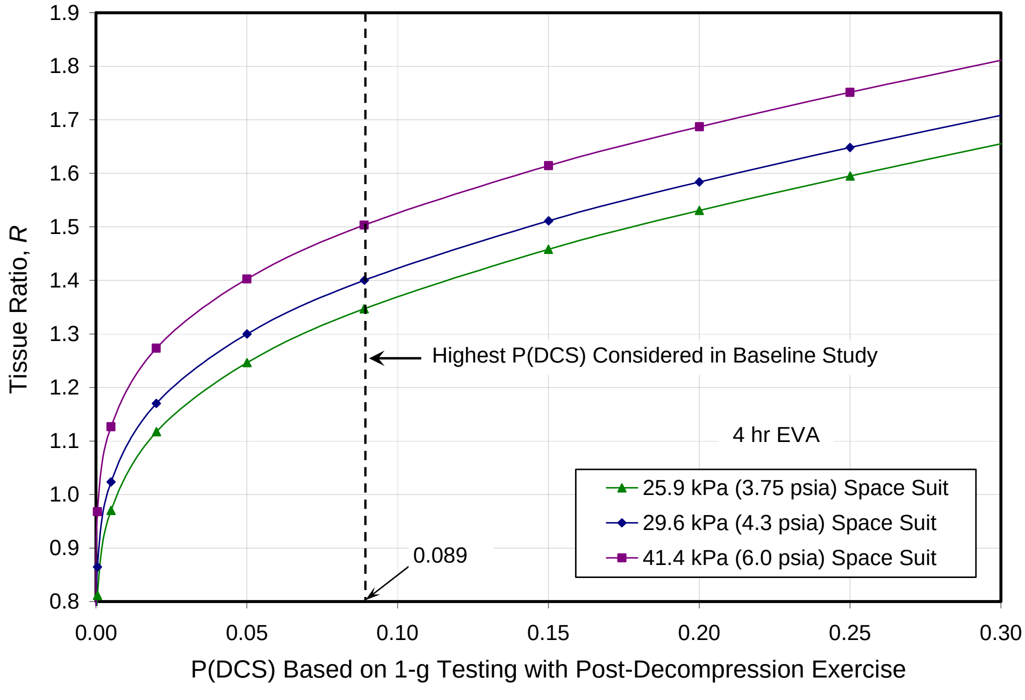

Figure 3-3. Dependence of *R* value on P(DCS) for different space-suit pressures as predicted from a statistical model. For a given P(DCS), the *R* value increases with space-suit pressure.

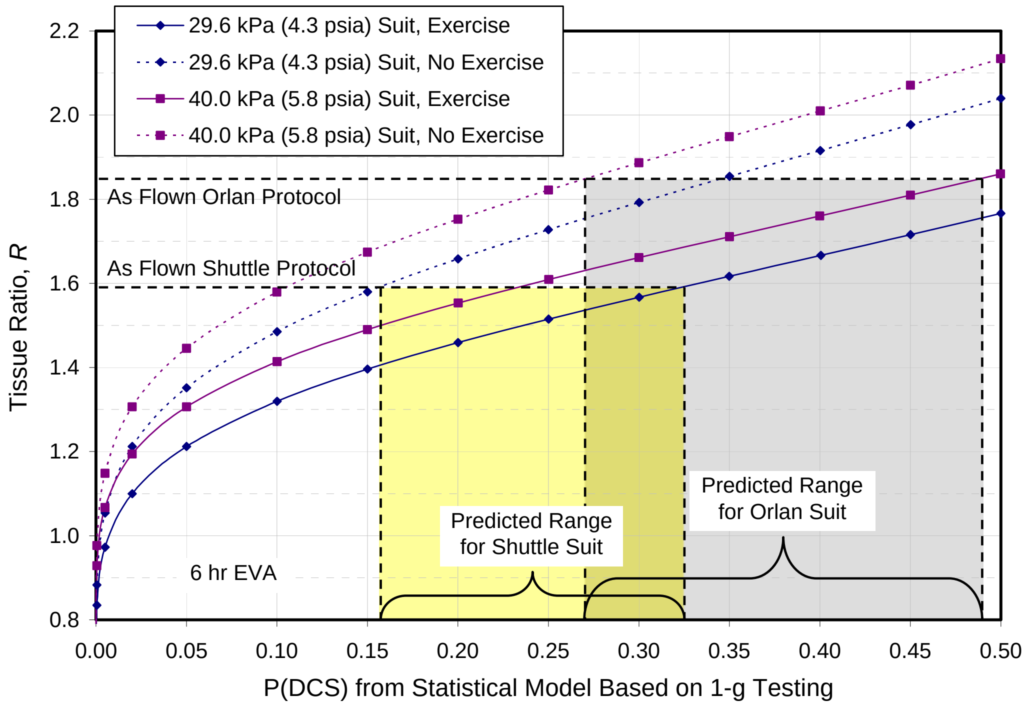

Figure 3-4. Predicted incidence of DCS for Shuttle and Orlan space suits from a statistical model based on 1-g testing.

The profound difference in reported DCS between ground testing and microgravity EVAs is not well understood. Potential contributing factors are listed below (Conkin (2001a, 2001c)):

- More efficient prebreathe due to exercise.
- Changes in the distribution of body fluids in microgravity that may influence the efficiency of denitrogenation or the likelihood of bubble formation in tissue and blood.
- Loss of micronuclei for bubble formation over extended exposure to microgravity.
- Lower body inactivity before and during exposure to reduced pressure (adynamia).
- Differences between EVA exercise and exercise performed during ground testing.
- Failure to notice minor DCS symptoms in space suits.

For surface exploration EVAs in partial gravity, will the incidence of DCS more closely resemble that in microgravity EVAs or in ground testing? If the incidence is closer to that in ground testing, then the maximum P(DCS) of 0.089 (8.9%) assumed in the baseline study would seem too high for a mission where a quick return to Earth is not possible. If the DCS incidence is closer to that in microgravity EVAs, then the assumed maximum P(DCS) may be too conservative. Additional research is needed to better define DCS risks and to establish and validate prebreathe protocols for surface exploration EVAs.

In Figures 3-5 through 3-7, the statistical model of Conkin and coworkers is used to generate curves of constant P(DCS) for space suit pressures of 25.9, 29.6, and 41.4 kPa. Each curve corresponds to a 60 minute prebreathe, and is based on a 4 hr EVA with exercise. The curve corresponding to the maximum P(DCS) assumed in the baseline study (P(DCS) = 0.089) is shown bolded and is used to define the resultant cabin atmosphere design space in Figures 3-6 and 3-7. This results in an expansion of the design space for the 41.4 kPa space suit relative to that in Figure 2-12. No design space exists for the 25.9 kPa space suit (Figure 3-5) with the currently defined bounds. The curves of constant P(DCS) provide an indication of the sensitivity of the atmosphere design space to the acceptable level of DCS risk.

As a final topic in this section, a second statistical model of Conkin (2001a) provides insight into the benefits of a minimum oxygen prebreathe on the prevention of serious (Type II) DCS. Serious DCS includes pulmonary, neurological, and cardiovascular disturbances that would end a test early for a subject (Conkin (2001a)). The incidence of serious DCS was found to correlate best with an *R* value based on a tissue compartment with a 180 minute half-time for nitrogen elimination (*R*(180)). Predictions of the model for various prebreathe times are shown in Table 3-3 for a 4 hr EVA with exercise in a 29.6 kPa space suit. Although each prebreathe results in the same value of *R*(360) (starting from different atmospheres), the value of *R*(180) decreases with prebreathe time, resulting in a significant reduction in P(serious DCS). The impact of a minimum oxygen prebreathe on tissues with a faster half time (which may include the brain and spinal cord) would be even greater. These results provide rationale for the 60 minute prebreathe assumed in this study.

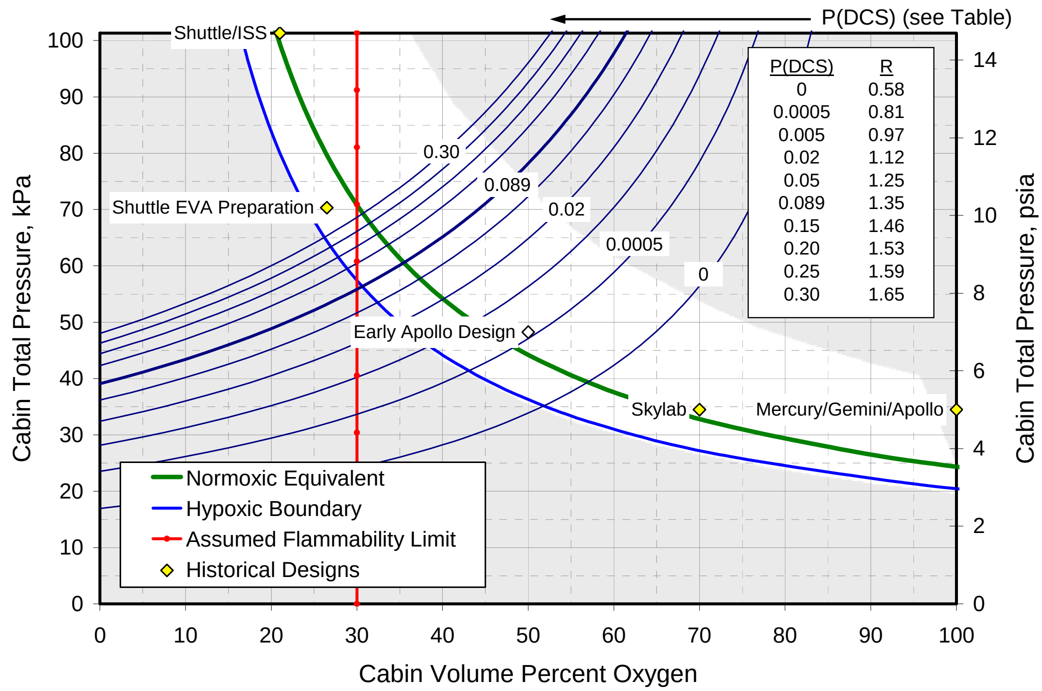

Figure 3-5. Curves of constant DCS probability for a 25.9 kPa (3.75 psia) space suit with a 60 minute prebreathe. Calculation based on 4 hr EVA with exercise. No design space exists for this space suit pressure within current bounds.

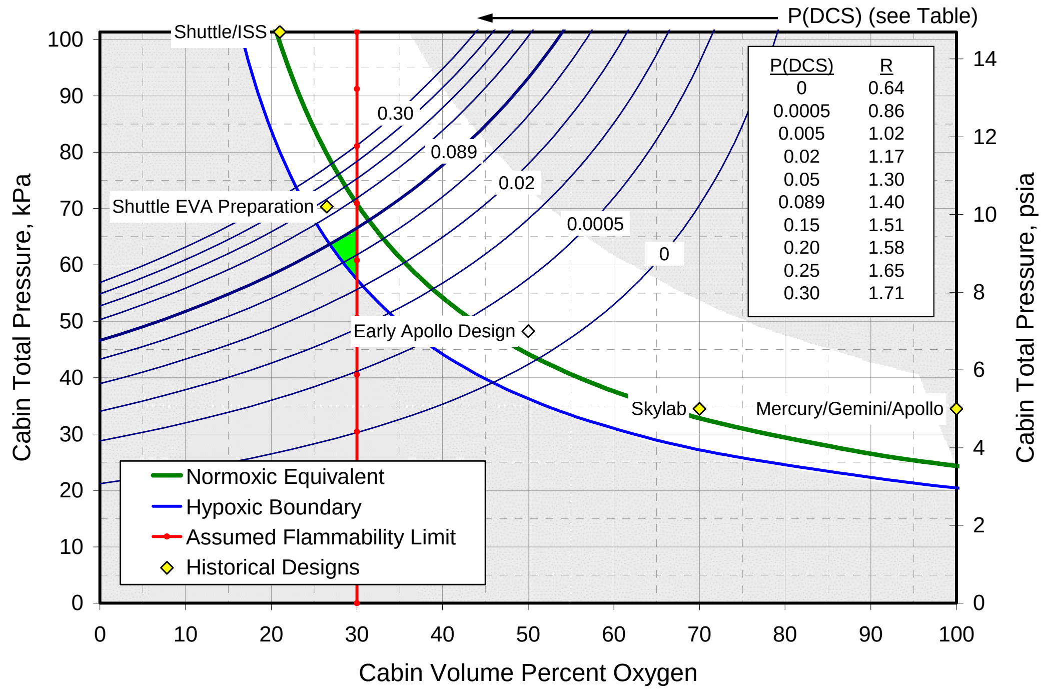

Figure 3-6. Curves of constant DCS probability for a 29.6 kPa (4.3 psia) space suit with a 60 minute prebreathe. Calculation based on 4 hr EVA with exercise. Resultant design space is shown shaded (green).

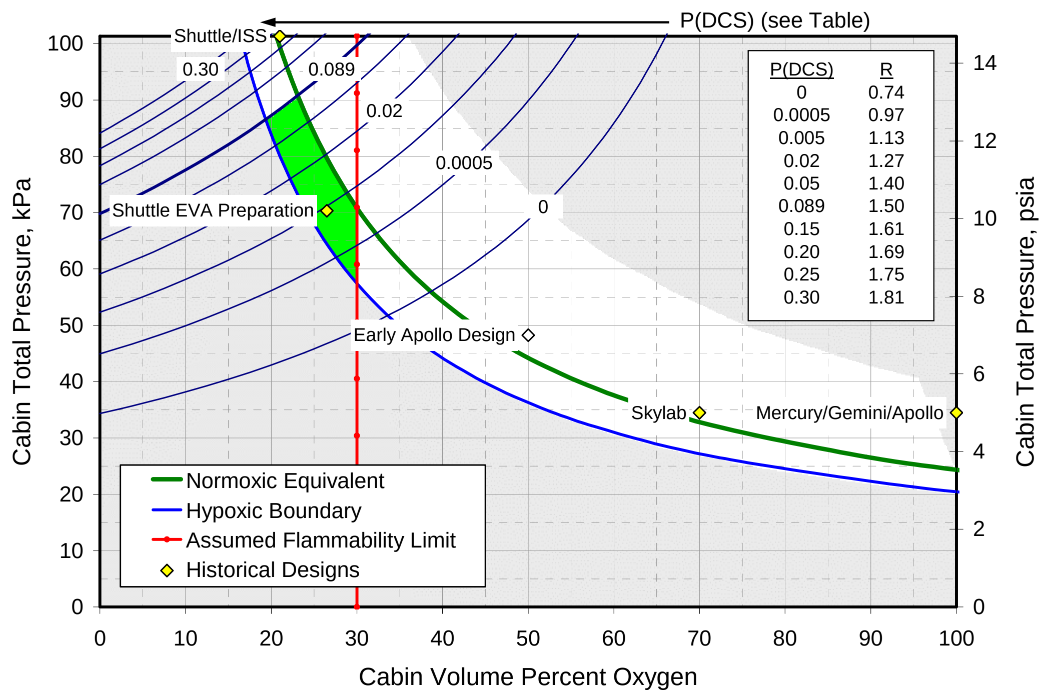

Figure 3-7. Curves of constant DCS probability for a 41.4 kPa (6 psia) space suit with a 60 minute prebreathe. Calculation based on 4 hr EVA with exercise. Resultant design space is shown shaded (green).

Table 3-3. Predicted Dependence of Serious DCS on Oxygen Prebreathe Time

Prebreathe Time, min	*R*(360)[a]	*R*(180)[b]	P(serious DCS)[c]
0	1.40	1.40	0.0046
30	1.40	1.32	0.0036
60	1.40	1.25	0.0028
90	1.40	1.18	0.0022
120	1.40	1.11	0.0017
150	1.40	1.05	0.0013
180	1.40	0.99	0.0010
210	1.40	0.93	0.0008
240	1.40	0.88	0.0006

[a]*R* value for a tissue compartment with a 360 minute half-time for nitrogen elimination.
[b]*R* value for a tissue compartment with a 180 minute half-time for nitrogen elimination.
[c]Based on a 4 hr EVA with exercise in a 29.6 kPa (4.3 psia) space suit.

3.4 Space Suit Pressure Design

It has been shown above that increasing the space suit pressure increases the cabin atmosphere design space and allows a lower cabin oxygen concentration. The primary penalty for increasing the space suit pressure with current technology is a reduction in space suit mobility, particularly in the gloves. A reduction in space suit mobility can result in increased astronaut fatigue during EVAs and reduced mission productivity. Suit and consumable mass penalties with increasing space suit pressure may also be significant.

3.4.1 Variable-Pressure Space Suit

One possible design solution that has been considered is a variable-pressure space suit. A variable-pressure space suit would allow initial operation at a higher pressure to reduce the probability of DCS and to effectively extend the oxygen prebreathe time, while allowing the EVA astronaut to perform useful work that does not require high glove mobility (e.g., transiting to an exploration site). For tasks that require increased glove mobility, the suit pressure could be reduced, either for short periods or for the remainder of the EVA. As indicated in the previous section, the incidence of DCS depends on the time of exposure to a decompression stress. A significant potential advantage of a variable-pressure space suit would be the ability to increase the pressure immediately in response to DCS symptoms, thus providing a measure of in-situ hyperbaric treatment. Potentially significant disadvantages of a variable-pressure space suit include increased space suit complexity and mass, and reduced reliability. As noted in Table 1-1, the Russian Orlan space suit allows operation at two pressures: 40.0 kPa (5.8 psia) and 26.5 kPa (3.8 psia).

3.4.2 Hyperoxic Space Suit Atmosphere and Radiation

> *The tension of oxygen in cells at the time of radiation is an important determinant of the degree of severity of radiation damage, as in the presence of oxygen, the amount of oxidizing radicals increases, due to the fact that the oxygen molecule is a reaction partner for the primary radiolytic products. Oxygen always enhances the action of radiation.* [Baumstark-Khan (2001)]

One space suit design issue that may be significant, but that the authors have not seen discussed, is the potential impact of a hyperoxic (higher than normoxic) space suit atmosphere in combination with the increased radiation environment outside of the Earth's geomagnetic field. As stated in the above reference, oxygen at the cellular level is known to increase indirect radiation damage caused by the production of free radicals. The relation between the space suit oxygen pressure, cellular oxygen levels, and radiation exposure risks during EVAs appears to be an area for investigation and resolution. If significant, this issue could weigh strongly against the use of a higher space suit pressure.

4 The Next Steps

Conclusions from the baseline study that were presented in Section 2.5 are not substantially altered by the extensions discussed in Section 3. The extensions do further emphasize, however, the need for expert consensus and research to better quantify spacecraft and space suit atmosphere requirement drivers. The continuing role of research as part of the envisioned atmosphere selection process is indicated in Figure 1-1. Risk statements and associated research questions contained in the NASA Bioastronautics Roadmap (NASA, 2005) motivate much of the necessary research.

After defining working bounds on the spacecraft cabin atmosphere design space, the next step envisioned in Figure 1-1 is the selection of candidate atmosphere designs for more detailed studies. Some candidates for spacecraft and space suit atmosphere designs are presented in Section 4.1.

The final step of Figure 1-1 involves more detailed risk and optimization studies and requires an assessment of the impacts of atmosphere pressure and composition on spacecraft and space suit systems and operations. Many of these impacts have been previously investigated and discussed in both published and unpublished studies. A brief summary of engineering considerations derived from these studies is presented in Section 4.2. These studies complement the results presented here and form the basis for further detailed mission-system design studies.

4.1 Candidate Atmosphere Designs for Further Study

Figure 4-1 provides an expanded view of the spacecraft cabin atmosphere design space for three space suit pressures ranging from 29.6-41.4 kPa (4.3-6.0 psia). The 60-minute prebreathe bound for each space suit pressure was calculated for an iso-risk DCS probability of 0.089 using the statistical model of Conkin and coworkers (1996). The design space for each space suit pressure includes all of the shaded area below its corresponding prebreathe bound.

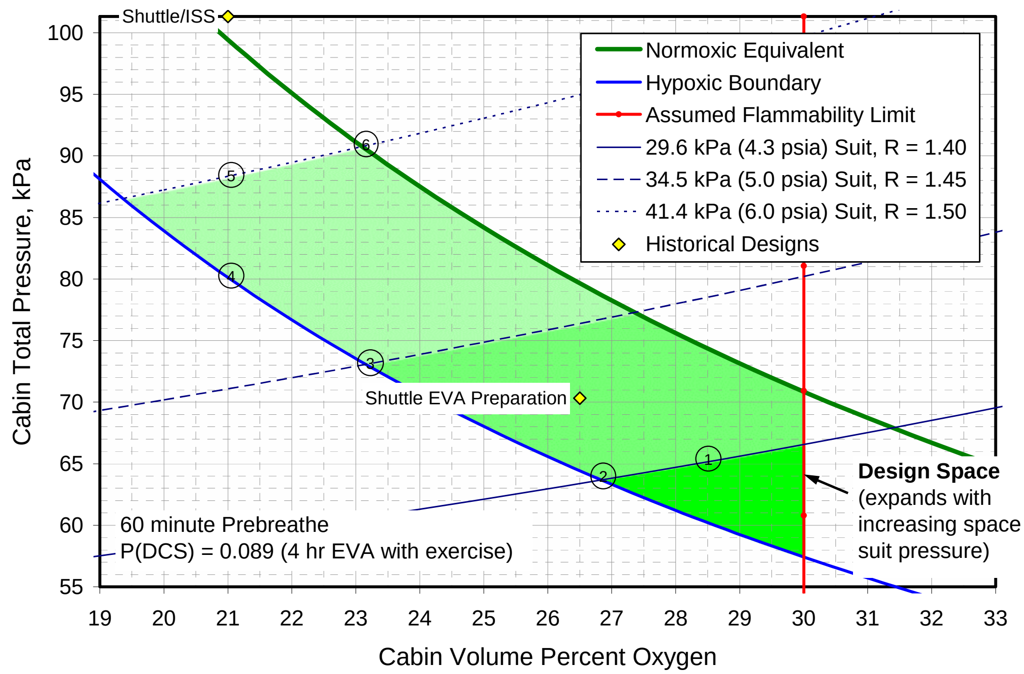

Figure 4-1. Spacecraft cabin atmosphere design space for 3 space suit pressures based on a 60 minute prebreathe and P(DCS) of 0.089 for EVAs. Possible candidate atmosphere designs for initial study are indicated by number.

Six possible candidate atmosphere designs for initial study are indicated by number in Figure 4-1. Characteristics of these designs are presented in Table 4-1. The proposed designs emphasize minimizing the cabin oxygen concentration, and cover the range of space suit pressure from the current design (Designs 1 and 2) to a higher-pressure design (Designs 4 and 5) that results in an Earth-normal cabin oxygen concentration. Many other candidate designs are of course possible.

Table 4-1. Candidate Spacecraft and Space Suit Atmosphere Designs

Design No.	Cabin Pressure, kPa (psia)	Cabin Oxygen Concentration, volume %	EVA Suit Pressure, kPa (psia)	General Characteristics
1	65 (9.4)	28.5	29.6 (4.3)	Current space suit pressure. Cabin atmosphere well above hypoxic boundary, but less than normoxic. May allow use of materials certified to 30% oxygen with tight spacecraft operating control bands.
2	64 (9.3)	26.8	29.6 (4.3)	Lowest cabin oxygen concentration with current space suit pressure; at hypoxic boundary.
3	73 (10.6)	23.2	34.5 (5.0)	Moderate increase in space suit pressure with lower cabin oxygen concentration; at hypoxic boundary.
4	80 (11.6)	21	41.4 (6.0)	Higher space suit pressure with Earth-normal cabin oxygen concentration; equivalent to 1829-m (6000-ft) Earth atmosphere. Lower DCS risk. Ground testing may be facilitated.
5	88.5 (12.8)	21	41.4 (6.0)	Higher space suit pressure with Earth-normal cabin oxygen concentration; well above hypoxic boundary. Ground testing may be facilitated.
6	91.0 (13.2)	23.1	41.4 (6.0)	Higher space suit pressure. Normoxic cabin atmosphere; slightly elevated oxygen concentration.

4.2 Engineering Considerations in Spacecraft and Space Suit Atmosphere Design

The topic of spacecraft and space suit internal atmosphere design has been examined numerous times since the beginning of the human spaceflight program. In addition to the physiological and key materials areas examined above, many other engineering factors must be considered before a final atmosphere design can be selected. The following sections highlight some of the most important of these considerations, and summarize the conclusions from roughly four decades of research and analysis. The reader is encouraged to examine the many references in Section 5 for more detailed information.

4.2.1 Cabin Structural Mass

Key drivers for structural mass of the cabin are thickness required for containing internal pressure, structural integrity to withstand launch and re-entry loads, radiation shielding, and meteoroid protection. Which factor ultimately dominates is necessarily mission (or spacecraft) specific. Roth (1967, 1968) concluded that at cabin pressures below about 34.5-48.3 kPa (5-7 psia), launch loads and meteoroid protection determine the minimum wall thickness, whereas at higher pressures (48.3-101.3 kPa (7-14.7 psia)) it is the wall stresses due to internal pressure that set the required thickness.

Brown (1991) reported that for a lunar habitat launch loads dominate over internal pressure up to 101.3 kPa (14.7 psia), and that additional thickness beyond that required for launch loads would be required for micrometeoroid protection. They also note that the internal pressure may contribute to structural stiffening, which may help to reduce required mass.

NASA (1992) reported that for a lunar vehicle design, launch loads were the most significant driver of the structure, over internal pressure and micrometeoroid protection. They also note that internal pressure was not a major weight or cost driver for the Apollo command module structure, and that the Space Station Freedom habitat structural design was similarly driven by launch loads. Their overall conclusion was that "total weight impacts due to changing the cabin pressure for the crew module should not be a driving consideration in selecting the crew module cabin pressure."

Radiation shielding was also discussed in Section 2.3.2.

4.2.2 Atmosphere Leakage

There are two classes of leakage to consider: the relatively fast leakage caused by a wall penetration with a large diameter relative to the wall thickness (orifice-type flow), and the inevitable slow leakage around fittings and seals (capillary type flow). Leakage of both types increases as cabin pressure increases, but the leakage rates vary differently with atmosphere composition.

For rapid decompression from 34.5-48.3 kPa (5-7 psia) due to orifice-type flow, Roth (1967) calculated that an O_2/N_2 mixture would take the longest time to decompress to a minimum tolerable O_2 partial pressure, while pure O_2 would reach the minimum tolerable partial pressure most quickly. When comparing N_2 and helium (He) at equivalent compositions and pressures, N_2 had a slight overall advantage as a diluent in rapid decompression.

For slow seal leakage, atmosphere composition was calculated to have little effect on mass loss when comparing pure O_2 and O_2 with helium, neon and nitrogen diluents at 34.5-48.3 kPa (5-7 psia) (Roth (1967)). Douglas (1966), however, presented leakage data that indicated the total seal leakage loss by weight of O_2/N_2 is greater than that of O_2/He, with the difference increasing as cabin pressure increases. Loss of oxygen was higher for the O_2/He mixture, however.

Back diffusion of CO_2 through leakage paths for a Mars habitat (Mars atmosphere is 95% CO_2, at 0.76 kPa) was examined by Jeng (2003), and it was found that the back diffusion of CO_2 is negligible compared to the outward leakage rate at a cabin pressure of 62.1 kPa (9 psia).

4.2.3 Makeup Gas Systems

As noted above, higher cabin pressure increases seal leakage and therefore required makeup gas regardless of composition. Of the composition options, using helium as a diluent results in the lowest mass of re-supply gas (Douglas (1966)); however seal leakage is also highest with helium, and the two effects may offset each other (Brown (1991)). In general, lower pressures reduce the air mass required for initial pressurization, repressurization, and resupply (McCarthy (1991)).

4.2.4 Thermal Control Systems

Atmosphere pressure affects thermal control systems through its impact on duct size and heat transfer capacity. For equivalent heat transfer with the crew and heat-generating equipment, the same mass flow rate of atmosphere will be required regardless of pressure. Thus, at lower cabin pressure the required volumetric flow rate is higher. The result is increased fan power or larger ducts or a combination of both.

Although the lower pressure means lower leakage rates and lower initial weight of cabin gas, NASA (1992) concluded that the weight penalty associated with the increased fan power (at constant duct size) is the dominant factor. Paul (2004) conducted a study in which Transhab- and X-38-type fan/duct systems were analyzed at pressures from 101.3 kPa (14.7 psia) to 55.2 kPa (8.0 psia). It was concluded that there is a slight advantage in equivalent system mass for increasing duct size versus increasing fan speed to arrive at the same mass flow rate. Paul also used computational fluid dynamics modeling to predict the air-to-cabin-wall heat transfer coefficient and average wall temperature at reduced pressures. It was found that at constant linear velocity the heat transfer coefficient decreases approximately 2.5% for each 6.9 kPa (1 psi) decrease in operating pressure, resulting in a decrease of approximately 0.04 K/kPa (0.5 °F/psi) in cabin wall temperature.

Lin (1991) concluded that the power penalty to the air cooling subsystem due to reduced pressure puts a practical minimum on cabin pressure of around 50.7 kPa (7.35 psia). It was also noted that at lower pressures, condensing heat exchangers tend to over-condense the humidity or under-cool the dry air to remove the same sensible heat, thus extra equipment may be required to re-humidify or further cool the air for crew comfort.

Roth (1967) found that O_2/He mixtures at reduced pressures had the lowest total thermal control system power compared to O_2 and O_2/N_2 atmospheres. Incorporated into the overall environmental control and life support system, O_2/He had the best equivalent mass, followed by pure O_2, and finally O_2/N_2. For the system Roth studied, however, the overall differences were only about 3% of the total system weight.

4.2.5 Life Support Systems

Lin (1991) surveyed the impacts of cabin pressure on physicochemical life support system components. He concluded that CO_2 reduction and removal systems and trace contaminant control systems, while currently designed and tested assuming 101.3 kPa (14.7 psia) pressure, should be able to operate at reduced pressures with little or no modification. Pressure has a small impact on oxygen generation rates because as the pressure is lowered the leak rate decreases but the concentration of oxygen in the leaking atmosphere is greater. This effect is small compared to the crew’s overall metabolic usage. Nitrogen make-up decreases as pressure decreases, thus the size of this system decreases with cabin pressure.

For aerobic biological waste processing systems that have been developed and tested using air, modifications may be required if they are to run on a cabin atmosphere with a different oxygen concentration (Paul (2005)). Alternatively, if they must be run on a 21% oxygen feed, a dedicated gas feed or blending system might be required. Variation in feed O_2 composition may lead to different choices of microbes for a given application.

4.2.6 Reliability Issues

Roth (1967) noted that reliability of partial-pressure sensing instruments is important in maintaining composition of mixed atmospheres, whereas a pure oxygen atmosphere only requires a pressure sensor. (This may no longer be a major issue, but at that time, reliable, flight-certifiable partial-pressure sensors were only in development.)

4.2.7 Laboratory Science

It has been recognized that having cabin atmospheres other than earth-normal can cause added complexities for laboratory science experiments (Roth (1967), Bailey (1989), Brown (1991), Morgenthaler (1994), Kosmo (2000)). Comparison of flight experiments carried out in different atmospheres with control experiments that were conducted on the ground at normal atmospheric conditions is complicated because the effects of different pressure or composition on experimental variables may not be known. On the other hand, conducting experiments on the ground at flight conditions other than normal atmospheric pressure and composition adds time and expense to the experimental programs. In addition, the use of off-the-shelf laboratory equipment may be limited by lower pressure or higher oxygen concentrations.

4.2.8 Crew Thermal Comfort Zone

Because of helium's high thermal conductivity, atmospheres using it as a diluent result in increased loss of body heat for a clothed crewmember and an increase in the temperature required for crew comfort. For a crew wearing light to medium clothing, the average comfort-zone temperatures were approximately 3-4 K (5-7 °F) higher for atmospheres using oxygen/helium as compared to oxygen/nitrogen atmospheres at 34.5-48.3 kPa (5-7 psia) (Douglas (1966)). This could be an advantage to the thermal control system since running the air and liquid cooling loop temperatures hotter would allow higher radiator temperatures and thus reduced radiator mass and volume.

4.2.9 Crew Verbal Communication

Noise levels must be low enough for the crew to be able hear audible warning alarms, and not cause degradation of performance due to irritation, sleep disruption, or hindrance of verbal communication (Kosmo (2000)). As noted above, reduced cabin pressure may result in the need for higher volumetric flow of air through thermal control and life support systems. This higher airflow may result in a higher ambient noise level. However, sound does not travel as well at lower pressures, and this may offset the effect of higher air velocities (Brown (1991), Morgenthaler (1994)). Use of more coldplating for cooling in place of forced airflow may help to reduce cabin noise.

In addition to ambient noise level, atmosphere pressure and composition may also affect crewmember's ability to communicate through speech (Brown (1991), Kosmo (2000)). Pressures below about 69.0 kPa (10 psia) result in degradation of a crewmember's ability to understand speech. This was demonstrated by speech intelligibility measurements during Skylab ground-based testing at 34.5 kPa (5.0 psia) with ambient noise sources. On-orbit speech intelligibility aboard Skylab may also have been affected by facial distortions caused by the micro-gravity environment. The use of helium as a diluent has also raised concerns about verbal communication. Because of helium's low density, it causes a high-pitched distortion of the sound coming from the vocal cords, which may result in decreased intelligibility. However, this effect may not be as pronounced at the lower pressures that have been considered for atmospheres using oxygen with a helium diluent.

4.2.10 Airlocks for EVA

There are two types of airlock: those that vent their atmosphere to space, and those that pump as much atmosphere as practicable back into the habitat before depressurizing. In the Apollo era, it was calculated that the added equipment and power for the atmosphere recovery system would typically pay off if the mission involves three to six EVAs or more (Douglas (1966)). The venting-type of airlock favors lower habitat pressure, because less mass is vented in each depressurization. For the recovery-type of airlock the initial pressure is less important than the final pressure before the lock is opened. The amount of mass that is vented is directly proportional to the final pressure, but there is a tradeoff because lower pressures require more vacuum pump power. Power expended during the beginning of depressurization is much lower than that expended when the airlock pressure reaches low values (3.4-6.9 kPa (0.5-1.0 psia)) (Brown (1991)).

4.2.11 Fire Detection and Suppression

Fire suppression becomes more difficult as oxygen concentration increases (Brown (1991), Martin (1993), NASA (1993)). This is because more inert gas or fire suppressant must be introduced to reduce the oxygen concentration to the point where combustion is not sustained. For oxygen concentrations above 30%, water is generally the only effective fire suppressant (Pedley (2005)). Although fire detection may be aided by the increased ventilation flow in lower pressure cabins, flame propagation is enhanced by higher air velocities.

4.2.12 Off-gassing

Toxicological assessments of spacecraft atmospheres are based on contaminant levels expressed as mass per unit volume (mass concentration; mg/m^3) (NASA (2000)). Although the vapor pressure (and thus equilibrium mass concentration) of a volatile contaminant does not change with cabin atmosphere total pressure, the rate of off-gassing may depend on factors such as local air flow and pressure changes that are related to atmosphere pressure selection. For oxidative breakdown products, the oxygen partial pressure in the atmosphere may influence the contaminant generation and off-gassing rate.

4.2.13 Food Packaging and Processing

Food packaging may be affected by below-sea-level pressures because the trapped air in the package will expand in the reduced cabin pressure. This problem can be alleviated for some foods by vacuum packaging, but other foods (such as bread) cannot be vacuum packaged and maintain their palatability (Brown (1991), Kosmo (2000)). Another solution would be to construct a food processing facility that operates at the same pressure as the cabin atmosphere, but this may be an expensive alternative.

Also of concern is the effect that reduced pressure has on cooking and sanitization temperatures. Water boils and food cooks at lower temperatures in reduced pressures, thus cooking times may be increased. Depending on the cabin pressure, pressure cookers might be needed to speed food preparation and generate temperatures high enough to sanitize food preparation equipment (Jeng (2000)).

4.2.14 Plant Growth

Plant growth, whether for food production or life support revitalization, is affected by pressure and the concentrations of oxygen and carbon dioxide (Brown (1991), Corey (2002)). There are two engineering approaches to growing plants: integrating them into the human habitat, or segregating them into their own habitat that is optimized for their purpose.

Having plants in the human habitat has certain intangible psychological benefits, but may not provide the optimal conditions for the plants' purpose of food production or regenerable life support. Tending to them, however, is relatively easy because they are nearby in the same cabin atmosphere.

Plant growth is enhanced by low pressures (5-50 kPa), low O_2 partial pressures (2-5 kPa), and moderately elevated CO_2 partial pressures (~ 0.1 kPa). However, the optimal conditions for certain plants may be outside of the habitable range for humans, which are roughly 50-101 kPa total pressure, 15-30 kPa O_2 partial pressure, and 0-0.7 kPa CO_2 partial pressure. There is the possibility that optimal plant growth conditions may allow the use of lightweight, low-pressure growth chambers on the moon or Mars. A disadvantage to this approach is that when human tending of the plants is required, prebreathing and airlocks, problems similar to EVA, may be required. In addition, if the plants are used for air or water revitalization, power and infrastructure will be required for transfer of the air/water to and from the plant chamber (Jeng (2000)).

Thus, we see that the decision of space cabin atmospheres is a rather complex one. It must be tailored to the vehicle, to the mission, and to the state of knowledge regarding many physical and biochemical variables. The more complex space station and interplanetary missions will no doubt add to the confusion. However, as in most scientific areas, the period of confusion leads to one of more complete understanding, simplification, and utilization. The hurried confusion of space science is no exception.
[Roth (1964)]

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6 Appendix – Alveolar Gas Equation

The Alveolar Gas Equation relates the oxygen partial pressure within the alveoli of the lung, the site of oxygen transport to the blood, to the oxygen partial pressure within the breathing atmosphere (inspired air). This equation is found in standard physiology textbooks, but in a form that neglects the partial pressure of carbon dioxide in the inspired air. Because elevated carbon dioxide levels generally exist in spacecraft internal atmospheres, this assumption may not be valid. A general form of the Alveolar Gas Equation is derived below that includes the effect of the inspired carbon dioxide partial pressure.

6.1 Respiratory Gas Partitioning

With each breath, a volume of air is inspired (subscript I) that is partitioned between active alveoli (subscript A) and dead space (subscript D). The latter does not participate in exchange of gasses other than water vapor. The dead space includes conducting airways (anatomic dead space) and poorly perfused alveoli (physiologic dead space). In a normal breath at rest, the volume of air inspired is referred to as the tidal volume V_T:

$$V_\mathrm{T} = V_\mathrm{A} + V_\mathrm{D} \tag{6-1}$$

Expired air (subscript E) includes contributions from both the alveolar volume and dead space volume. The moles of oxygen and carbon dioxide in the expired air can be expressed in terms of the molar concentration, c, in each volume:

$$c_\mathrm{EO2} V_\mathrm{T} = c_\mathrm{AO2} V_\mathrm{A} + c_\mathrm{DO2} V_\mathrm{D} \tag{6-2}$$

$$c_\mathrm{ECO2} V_\mathrm{T} = c_\mathrm{ACO2} V_\mathrm{A} + c_\mathrm{DCO2} V_\mathrm{D} \tag{6-3}$$

Similar equations can be written in terms of the partial pressure, p, assuming that the expired gas from each volume has equilibrated to body temperature:[8]

$$p_\mathrm{EO2} V_\mathrm{T} = p_\mathrm{AO2} V_\mathrm{A} + p_\mathrm{DO2} V_\mathrm{D} \tag{6-4}$$

$$p_\mathrm{ECO2} V_\mathrm{T} = p_\mathrm{ACO2} V_\mathrm{A} + p_\mathrm{DCO2} V_\mathrm{D} \tag{6-5}$$

On a dry basis, the molar fraction, F, of oxygen and carbon dioxide in the dead space are assumed to be the same as in the inspired air. Then,

$$F_\mathrm{IO2} \equiv \frac{p_\mathrm{IO2}}{(P_\mathrm{B} - p_\mathrm{IH2O})} = \frac{p_\mathrm{DO2}}{(P_\mathrm{B} - p_\mathrm{DH2O})} \tag{6-6}$$

$$F_\mathrm{ICO2} \equiv \frac{p_\mathrm{ICO2}}{(P_\mathrm{B} - p_\mathrm{IH2O})} = \frac{p_\mathrm{DCO2}}{(P_\mathrm{B} - p_\mathrm{DH2O})} \tag{6-7}$$

[8] From the ideal gas law, $c = p/R_\mathrm{g}T$, where R_g is the gas constant and T is the absolute gas temperature.

Combining equations 6-6 and 6-7 with equations 6-4 and 6-5 yields

$$p_{\mathrm{EO2}}V_{\mathrm{T}} = p_{\mathrm{AO2}}V_{\mathrm{A}} + p_{\mathrm{IO2}}V_{\mathrm{D}}\left(\frac{P_{\mathrm{B}} - p_{\mathrm{DH2O}}}{P_{\mathrm{B}} - p_{\mathrm{IH2O}}}\right) \tag{6-8}$$

$$p_{\mathrm{ECO2}}V_{\mathrm{T}} = p_{\mathrm{ACO2}}V_{\mathrm{A}} + p_{\mathrm{ICO2}}V_{\mathrm{D}}\left(\frac{P_{\mathrm{B}} - p_{\mathrm{DH2O}}}{P_{\mathrm{B}} - p_{\mathrm{IH2O}}}\right) \tag{6-9}$$

6.2 Time-Average Molar Balances

Molar gas flows active in respiratory exchange are illustrated in Figure 6-1.

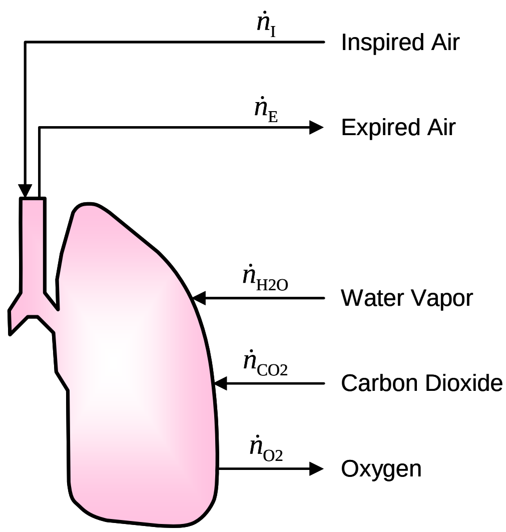

Figure 6-1. Respiratory gas exchange.

A time-average molar balance yields

$$\dot{n}_{\mathrm{E}} = \dot{n}_{\mathrm{I}} + \dot{n}_{\mathrm{H2O}} + \dot{n}_{\mathrm{CO2}} - \dot{n}_{\mathrm{O2}} \tag{6-10}$$

Similar balances on oxygen, carbon dioxide, and water result in the following equations:

$$\left(\frac{p_{\mathrm{EO2}}}{P_{\mathrm{B}}}\right)\dot{n}_{\mathrm{E}} = \left(\frac{p_{\mathrm{IO2}}}{P_{\mathrm{B}}}\right)\dot{n}_{\mathrm{I}} - \dot{n}_{\mathrm{O2}} \tag{6-11}$$

$$\left(\frac{p_{\mathrm{ECO2}}}{P_{\mathrm{B}}}\right)\dot{n}_{\mathrm{E}} = \left(\frac{p_{\mathrm{ICO2}}}{P_{\mathrm{B}}}\right)\dot{n}_{\mathrm{I}} + \dot{n}_{\mathrm{CO2}} \tag{6-12}$$

$$\left(\frac{p_{\mathrm{EH2O}}}{P_{\mathrm{B}}}\right)\dot{n}_{\mathrm{E}} = \left(\frac{p_{\mathrm{IH2O}}}{P_{\mathrm{B}}}\right)\dot{n}_{\mathrm{I}} + \dot{n}_{\mathrm{H2O}} \tag{6-13}$$

Assuming that expired gas from each volume is saturated with water vapor at body temperature,

$$p_{\mathrm{EH2O}} = p_{\mathrm{DH2O}} = p_{\mathrm{AH2O}} = 47 \text{ mmHg} \tag{6-14}$$

6.3 Resultant Equations

Equations 6-8 through 6-14 provide all of the relations necessary to derive the Alveolar Gas Equation. After considerable algebraic manipulations to eliminate variables, the following general form is obtained:

$$p_{\mathrm{AO2}} = \frac{p_{\mathrm{IO2}}\left[p_{\mathrm{ACO2}}(1-RQ) + RQ(P_{\mathrm{B}} - p_{\mathrm{AH2O}})\right] + p_{\mathrm{ICO2}}(P_{\mathrm{B}} - p_{\mathrm{AH2O}}) - p_{\mathrm{ACO2}}(P_{\mathrm{B}} - p_{\mathrm{IH2O}})}{p_{\mathrm{ICO2}}(1-RQ) + RQ(P_{\mathrm{B}} - p_{\mathrm{IH2O}})} \tag{6-15}$$

where *RQ* is the respiratory quotient (or, more appropriately, respiratory exchange ratio) that can be defined as follows:

$$RQ = \frac{\dot{n}_{\mathrm{CO2}}}{\dot{n}_{\mathrm{O2}}} \tag{6-16}$$

With the assumption that $p_{\mathrm{ICO2}} = 0$, equation 6-15 reduces to the more familiar form found in physiology textbooks:

$$p_{\mathrm{AO2}} = F_{\mathrm{IO2}}(P_{\mathrm{B}} - p_{\mathrm{AH2O}}) - p_{\mathrm{ACO2}}\left[F_{\mathrm{IO2}} + \frac{(1-F_{\mathrm{IO2}})}{RQ}\right] \tag{6-17}$$

The alveolar nitrogen partial pressure, p_{AN2}, can be obtained from the sum of partial pressures:

$$p_{\mathrm{AN2}} = P_{\mathrm{B}} - p_{\mathrm{AO2}} - p_{\mathrm{AH2O}} - p_{\mathrm{ACO2}} \tag{6-18}$$

7 Abbreviations and Acronyms

AIM	Advanced Integration Matrix
ASTM	American Society for Testing and Materials
CO_2	carbon dioxide
DCS	Decompression Sickness
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
EVAs	Extravehicular Activities
ft	feet
GCR	Galactic Cosmic Radiation
He	helium
ISS	International Space Station
kPa	kilopascals
m	meters
MAPTIS	Materials and Processes Technical Information System
min	minutes
mm Hg	millimeters of mercury
N_2	nitrogen
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association
O_2	oxygen
P(DCS)	probability of decompression sickness
P(serious DCS)	probability of serious (Type II) decompression sickness
psia	pounds per square inch absolute
QDM	Quick Don Mask
SPE	Solar Particle Event
U.S.	United States

8 List of Symbols

c	molar concentration
F	molar fraction (generally on dry basis)
$\dot{n}$	molar flow
P	total pressure
p	partial pressure
R	tissue ratio
R_g	ideal gas constant
RQ	respiratory quotient (respiratory exchange ratio)
T	absolute temperature
t	time
$t_{1/2}$	half-time for inert gas (nitrogen) elimination in specific body tissue type
V	volume of air
Subscripts (frequently combined)[9]	
A	alveolar
B	barometric (ambient)
CO2	carbon dioxide
D	dead space
E	expired

[9] For example, p_{AO2} is the alveolar oxygen partial pressure.

H2O	water
I	inspired
N2	nitrogen
N2-Tissue	nitrogen in tissue
O2	oxygen
Suit	space suit
T	tidal

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13. ABSTRACT *(Maximum 200 words)*

The selection of spacecraft and space suit atmospheres for future human space exploration missions will play an important, if not critical, role in the ultimate safety, productivity, and cost of such missions. Internal atmosphere pressure and composition (particularly oxygen concentration) influence many aspects of spacecraft and space suit design, operation, and technology development. Optimal atmosphere solutions must be determined by iterative process involving research, design, development, testing, and systems analysis. A necessary first step in this process is the establishment of working bounds on the atmosphere design space.

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