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Recommendations for Exploration Spacecraft Internal Atmospheres:

The Final Report of the NASA Exploration Atmospheres Working Group

NASA Exploration Atmospheres Working Group

NASA Johnson Space Center, Houston

STS-114 Mission Specialist Stephen K. Robinson is attached to a foot restraint on the International Space Station's Canadarm2. Image credit: NASA

National Aeronautics and
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Johnson Space Center
Houston, TX 77058

October 2010

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Preface

This report is a result of work conducted during 2005 by the NASA Exploration Atmospheres Working Group (EAWG). It is intended for use by NASA offices and programs that are developing capabilities for human exploration of the moon, Mars, and the solar system.

The members of the EAWG are gratefully acknowledged for their active participation in the working group process and for their insightful contributions to this report. External reviewers are acknowledged for the comments and data they provided to the EAWG. The members of the EAWG support team, including technical analysts and workshop organizers, are acknowledged for their critical roles in the success of the EAWG.

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Acronyms

AHP	Analytical Hierarchy Procedure
CEV	crew exploration vehicle
CM	Command Module
CO2	carbon dioxide
COTS	commercial off-the-shelf
DCS	decompression sickness
EAWG	Exploration Atmospheres Working Group
EMI	electromagnetic interference
ESAS	Exploration Systems Architecture Study
ESMD	Exploration Systems Mission Directorate
EVA	extravehicular activity
FOM	figure of merit
FTA	fault tree analysis
HSWG	Human System Working Group
ISS	International Space Station
LEO	low-Earth orbit
LSAM	lunar surface access module
OCHMO	Office of the Chief Health and Medical Officer
P(DCS)	probability of decompression sickness
PFO	patent foramen ovale
PLSS	Portable Life Support System
psia	pounds per square inch, absolute
VSE	Vision for Space Exploration

Executive Summary

To enable missions to the moon and Mars, it is recommended that NASA's Constellation vehicles, habitats, and spacesuits employ an integrated set of internal atmospheres rather than a single design for all elements. These atmospheres must mitigate the risks of fire, decompression sickness (DCS), and hypoxia and enable crew excursions on planetary surfaces. The recommendations provided herein are not requirements and reflect technical considerations only.

The initial crew exploration vehicle (CEV) missions in low-Earth orbit, for crew and cargo transfer to the International Space Station (ISS), should operate within existing ISS and space shuttle standard atmosphere designs at 14.7 and 10.2 pounds per square inch, absolute (psia) nominal total pressures. For lunar sortie missions, the docked CEV and lander (also known as lunar surface access module [LSAM)], should operate at a nominal 10.2 psia total pressure, 26.5% oxygen concentration. These atmospheres ensure compatibility with that of the ISS, do not preclude contingency extravehicular activity (EVA), and do not significantly add to the cost or schedule burden of CEV development.

For surface operations, the lunar and Mars landers should also operate at a nominal 8.0 psia, 32% oxygen. This will require spacecraft interior materials flammability testing at a maximum oxygen concentration outside the existing shuttle/ISS database, and will add some cost for such testing. This atmosphere allows efficient EVA preparation and egress on the moon, and provides a nominal altitude equivalent of 5000 ft. All recommended nominal atmospheres are assumed to be at the center of a control box of ±0.2 psia total pressure and ±2.0% oxygen concentration. The lower end of the lander atmosphere control box may extend to equivalent altitudes over 6000 ft, which is outside the current NASA standard for hypoxic conditions.

It is especially important to note that these recommendations for the landers must be examined more closely prior to development of their requirements. For example, a comprehensive trade study to evaluate acceptable materials at elevated oxygen levels must be conducted to ensure that technical and programmatic considerations are assessed.

In-space and surface EVA suits should operate at a nominal 4.3 psia, 100% oxygen, which is consistent with current shuttle/ISS suits. The surface suit should also be able to operate at the lander pressure (8.0 psia) for treatment of DCS, at approximately 6.0 psia for rapid EVA egress, and at 3.5 psia in certain contingencies. All of these atmospheres are within current NASA physiological standards for anticipated suited durations at each condition.

The long-duration lunar and Mars surface habitats should operate at both a nominal 8.0 psia, 32% oxygen and at 7.6 psia, 32% oxygen (6500 ft equivalent altitude). This will allow the crew to adapt over an extended period of time to the lower pressure, which will then result in higher efficiency for EVA preparation and egress. The 7.6 psia nominal atmosphere is within the current aviation operational experience base, but would require a modification of the NASA standard on hypoxic conditions. It is especially important to note that these recommendations for surface habitats must be examined more closely prior to development of requirements for those elements.

The Mars transit vehicle should operate at nominal values of 14.7 psia, 21% oxygen and 10.2 psia, 26.5% oxygen. This leverages ISS long-duration physiological data and allows the crew to acclimate to a lower pressure prior to Mars arrival.

To support these recommendations, as soon as possible Constellation should institute a modified standard NASA flammability test to generate ignition threshold data for key spacecraft materials. This modified test will allow NASA to identify materials at risk from increases in oxygen concentration, minimize potential impacts, and allow for development of sound requirements for landers and habitats.

The Human Research, Technology Development, and Constellation Programs should initiate activities to enable these atmosphere designs (respectively, human research, technology development, and program-specific studies) to validate these recommendations for the Constellation habitable elements.

1 Exploration Atmospheres Working Group Background and Objectives

The Exploration Atmospheres Working Group (EAWG) was convened to formulate recommendations on the designs of habitable internal atmospheres for future exploration vehicles. This report describes the EAWG trade space as well as the outcome of systems analysis of candidate atmospheres. The results provided by the EAWG are designed as input to requirements for the near- and far-term vehicle development efforts within the Constellation Program, including the Crew Exploration Vehicle (CEV) Project.

1.1 Background

Over the past 47 years, NASA has developed and operated several types of human spacecraft and spacesuits to meet its mission needs. These vehicles have operated with internal habitable atmospheres ranging from the low-pressure, pure-oxygen environment of Mercury, Gemini, and Apollo to the current space shuttle and International Space Station (ISS) Earth sea-level pressure and oxygen content.

The Vision for Space Exploration (VSE) (NASA, 2004) specifies that NASA is to develop and execute human missions to the moon, to Mars, and beyond. It emphasizes a long-term approach to the human exploration of the solar system by NASA. Interplanetary human spacecraft, planetary landers, spacesuits, pressurized rovers, and surface habitats may be developed to accomplish this goal. Each of these new vehicles will contain a habitable atmosphere to support living and working activities of its human crew. Each atmosphere will be required to meet agency-level standards for health and safety, ensuring that risks to the human occupants are controlled to acceptable levels. To manage these risks as well as the overall programmatic costs, there is a need for a common design and development approach to optimize the systems engineering of multiple spacecraft – specifically their internal atmospheres.

NASA addressed this need through formal systems analysis. In 2004, a small systems analysis team at the Johnson Space Center identified atmosphere-related risks to human physiology, spacecraft design and materials, and mission operations. This team then constructed a trade space of atmosphere designs based on these risks and produced several candidate design points within that trade space that met the NASA design standards (Lange et al., 2005).

In 2005, the EAWG operated specifically within the framework of the VSE to refine the atmosphere trade space into a set of recommendations for exploration programs. This final report of EAWG activities and results is consistent with the objectives of the VSE and is designed to support Constellation Program needs.

1.2 Charter

The Exploration Systems Mission Directorate (ESMD), as part of the NASA inter-organizational Human System Working Group (HSWG), chartered the EAWG and tasked it to generate recommendations on the characteristics of internal atmospheres for exploration spacecraft, including spacesuits and planetary exploration vehicles. Appendix A provides a complete list of EAWG members.

The EAWG Implementation Plan, Appendix B, was generated in response to the ESMD request. This plan laid out EAWG objectives and a general plan for EAWG membership, activities, and products. The overall EAWG objective was described as to “refine the atmospheric design space to a relatively small domain such that atmospheric requirements for space-based systems can be specified.” Table 1 lists the discipline areas represented by the EAWG membership.

Table 1. Disciplines Represented in Exploration Atmospheres Working Group

Physiological and Medical
Environmental physiology
Extravehicular activity (EVA) physiology
Space medicine
Toxicology
Mission Operations
EVA operations
EVA systems
Exploration mission-systems architectures
Human factors
Safety and mission assurance
Vehicle and Habitat Systems
Active thermal control systems
Environmental control and life support systems
Food systems
Materials flammability and selection
Space radiation shielding
Spacecraft structures

1.3 Specific Objectives

As the EAWG formed and operated, more specific process- and product-oriented objectives were generated by its leadership to guide group activities and analytical efforts. These included to

- employ risk-based systems engineering analysis to achieve balanced risk mitigation.
- use a long-range view that considers multiple interacting mission systems.
- apply past NASA program experiences to make use of lessons learned and leverage flight-proven technologies and techniques.
- take advantage of insights and novel solutions available outside NASA.
- strive for multidiscipline consensus within the EAWG membership.
- identify the roles of research, technology development, and engineering in meeting the challenges presented in the ultimate selection of spacecraft atmospheres.

2 Exploration Atmospheres Working Group Process Overview

This section provides an overview of the process and analytical methods used by EAWG.

2.1 Exploration Atmospheres Working Group Activities

Soon after formation, the EAWG held its first general meeting on June 22, 2005 at the Johnson Space Center. EAWG members began their discussion and documentation of major risks related to atmosphere design.

EAWG analytical activities, which were initiated after the June meeting, led to the second general meeting on August 10-11, 2005 at the Center for Advanced Space Studies in Houston. EAWG members discussed their evaluations of multiple candidate atmospheres under consideration.

Additional analytical activities were conducted during September and October 2005. In lieu of a third meeting, a teleconference was held with the EAWG membership on October 4, 2005.

On November 1-3, 2005, the EAWG held a workshop to allow invited reviewers to provide inputs to its process. Immediately after the workshop on November 3, 2005, the EAWG held a meeting of its members on the results of the workshop and the production of this final report. The EAWG then held a teleconference on December 9, 2005 to discuss its recommendations. This concluded the EAWG general meetings.

2.2 Exploration Atmospheres Working Group Analysis – Overview

Three EAWG subgroups were formed to focus on specific risk areas, with each subgroup containing members from related disciplines. These subgroups were: Physiological and Medical Factors, Vehicle and Habitat Systems Factors, and Mission Operations Factors.

Several analytical methods were combined to form the systems engineering process supporting the EAWGs work. Fault tree analysis (FTA) was used to analyze the major risks identified by the EAWG. The Analytical Hierarchy Procedure (AHP) was employed to gather EAWG member evaluations of candidate atmosphere designs to assess the degree of consensus among members.

White papers were generated by EAWG members and associated NASA personnel to provide explanations of specific technical issues and design challenges. Gap analysis was performed to identify research, technology development, and engineering challenges as future work to support the ultimate selection and validation of exploration spacecraft atmospheres.

3 Exploration Atmospheres Working Group Analytical Foundation

This section provides references to materials that were considered fundamental or controlling for the EAWG trade study.

3.1 History of Spacecraft Atmospheres

Lange et al. (2005) summarized previous NASA spacecraft atmosphere designs and operations, as shown in Table 2.

Program	Cabin Pressure, kPa (psia)	Cabin Oxygen Concentration, volume %	EVA Suit Pressure,(1) kPa (psia)	EVA O_2 Pre-breathe Time, minutes	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(3)	In-suit
ISS/US	101.3 (14.7)	21	29.6 (4.3)	120-140	Mask and in-suit; staged w/exercise
				240(3)	In-suit
Salyut, Mir, ISS/Russian	101.3 (14.7)	21	40.0 (5.8)(2)	30	In-suit

References: Carson, et al. (1975), McBarron, et al. (1993), Waligora, et al. (1993), NASA (2002), NASA (2003).
(1) 100% oxygen.
(2) In earlier versions of the Orlan suit, the pressure could be reduced to 26.5 kPa (3.8 psia) for short-duration work regime.
(3) Under emergency conditions, a minimum of 150 minutes of unbroken prebreathe is recommended.

In addition to these steady-state design conditions, the Apollo Program provides a useful example of the transition of a spacecraft atmosphere between two operational conditions. In Biomedical Results of Apollo, Section II, Chapter 5, Environmental Factors (NASA, 1975), on-orbit transition of the Apollo spacecraft atmosphere is described. The document states: “Apollo preflight checkout procedures initially encompassed an overpressurization of the Command Module (CM) using 100 percent oxygen. After the Apollo fire, these procedures were modified, and a mixture of 60 percent oxygen and 40 percent nitrogen was used to reduce the fire hazard. The CM was launched with this gas composition, which eventually was built up to almost 100 percent oxygen, through leakage makeup with oxygen…". Figure 1, as excerpted from that document, illustrates a portion of that transition. The two curves (assumed to be upper/lower limits) show how the vehicle cabin atmosphere increased from a launch value of approximately 60% oxygen to the nominal flight atmosphere of 100% oxygen over an extended period in orbit and during lunar transit.

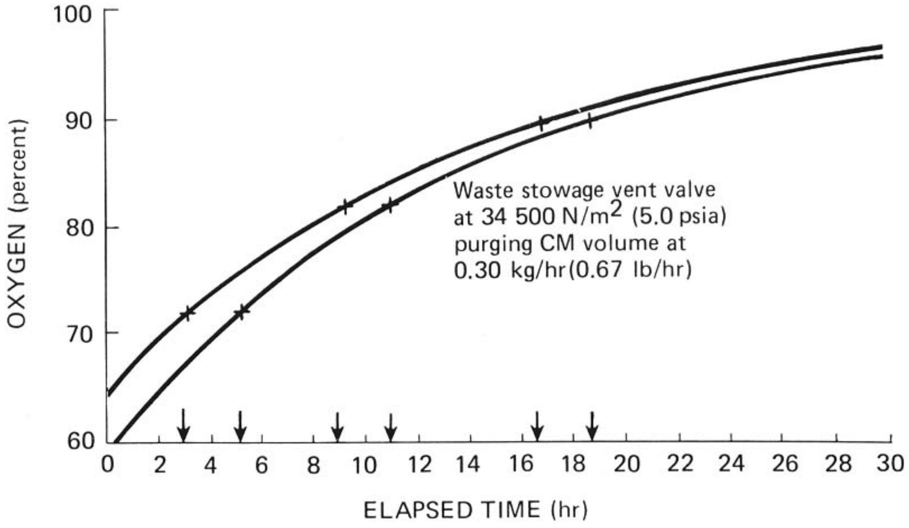


Figure 1. Apollo command module atmosphere on-orbit transition (Biomedical Results of Apollo, NASA, 1975).

3.2 Related Work

Lange et al., in their report "Bounding the Spacecraft Atmosphere Design Space for Future Exploration Missions" (2005), provided the major source of information used to initiate EAWG activities and analyses.

The Bioastronautics Roadmap (NASA, 2005) was a major source of research and technology issues as well as of topics for environmental physiology, EVA, and other areas related to spacecraft atmospheres. Some of the recommendations in this report may be used as inputs for updating research questions in the Bioastronautics Roadmap.

The NASA Exploration Systems Architecture Study (ESAS) (NASA, 2005) was conducted in parallel with the EAWG work. The ESAS data released during 2005, used by the EAWG as reference mission-systems information, are consistent with the recommendations in this report. The full ESAS report was not available to the entire EAWG during its analytical work, however.

The Exploration Extravehicular Activity (EVA) Suit Architecture Study was conducted in parallel with the EAWG work. Members of the EAWG also participated in this suit study. The recommended suit architecture was not published at the time of release of this report, although it is anticipated that the EAWG recommendations will be consistent with the suit architecture study results.

3.3 NASA Requirements and Technical Standards

NASA issues agency-level technical standards through the Office of the Chief Engineer and the Office of the Chief Health and Medical Officer. The NASA Human-Rating Requirements for Space Systems (NASA, 2005) is an integral part of the agency-level requirements process, and refers to various technical standards that must be applied in the spacecraft human-rating process.

NASA technical standards were used as sources of constraints for EAWG analyses and recommendations. NASA-STD-3000, Volume I, Revision B, (NASA, 1995) is invoked by the Human-Rating Requirements for Space Systems (NASA, 2005). This document provided the design space of all atmospheric pressures and compositions available to meet human constraints related to atmospheric pressure and oxygen content.

At the time of the EAWG work, agency-level human health standards were in preparation but were unpublished. An internal NASA document, which is invoked by the Human-Rating Requirements for Space Systems (NASA, 2005), was used as the existing source of medical standards. It requires hyperbaric treatment capability for crewmembers under certain mission scenarios. It also cites NASA-STD-3000 (NASA, 1995) for specifications of habitable atmospheres.

It is expected that NASA will baseline new space flight health standards in the near future. The effect of these new standards must be taken into account in the ultimate selection of exploration atmospheres by the Constellation Program. For example, if the agency were to impose standards in the areas of hypoxia or decompression sickness (DCS) that differ from those stated in an internal NASA documents, these new standards could affect the EAWG recommendations in this report.

NASA-STD-6001 (NASA, 1998) was also used as a source of information for the EAWG.

Another internal NASA document is also invoked by the Human-Rating Requirements for Space Systems (NASA, 2005). It levies a standard that “spacecraft and habitable modules shall be designed and operated so that atmospheric pressure and composition control systems maintain a habitable environment under all nominal and contingency operational scenarios.” It requires that “provisions shall be made to monitor and control oxygen, nitrogen, carbon monoxide, carbon dioxide, partial and total atmospheric pressure, and credible atmospheric contaminants,” and that “crew compartments shall be designed with forced ventilation to prevent stagnant air pockets from forming in crew-habitable areas of the compartment.”

Non-NASA technical standards related to human physiology, fire prevention, and other areas were sometimes considered, but these standards were not mandated or imposed on the EAWG process of deliberation and recommendation.

4 Trade Study

This section describes the specific trade study conducted by the EAWG. The intent was to refine the trade space provided by Lange et al., and to narrow the range of recommended atmospheres to be provided to the Constellation Program.

4.1 Identification of Candidate Atmospheres

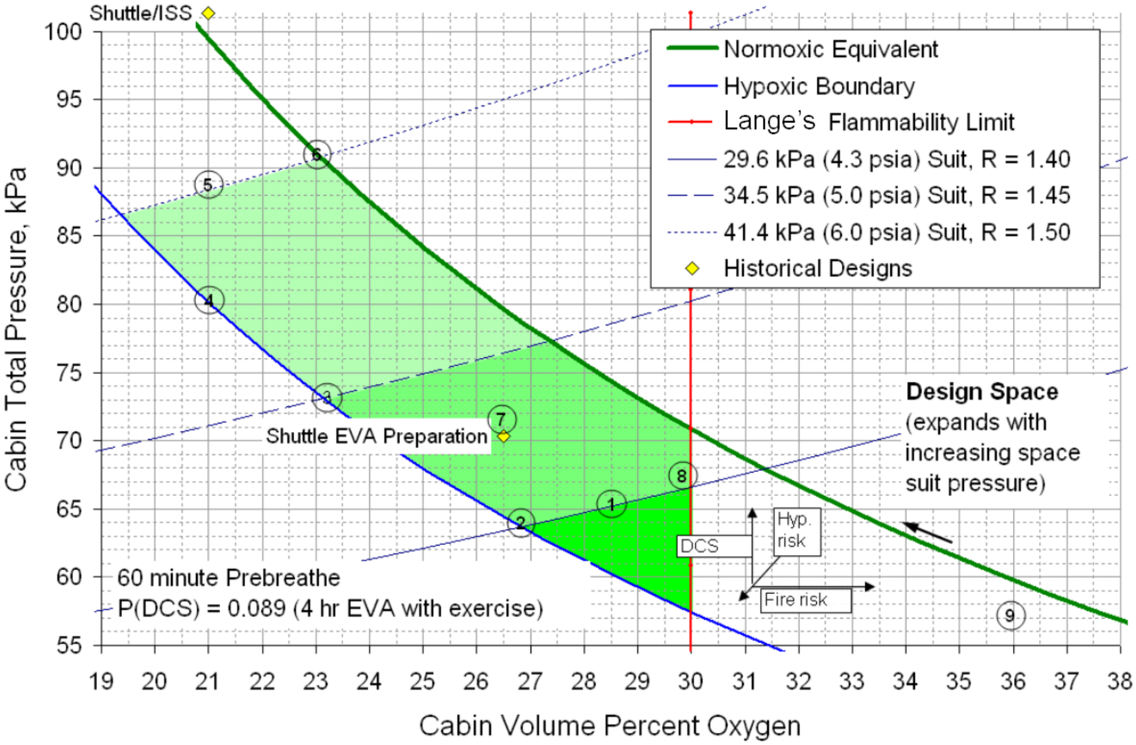
The EAWG began its deliberations using the six candidate atmosphere design points provided by Lange et al. The EAWG then added three more candidate design points, resulting in the set shown in Table 3 and figure 2.

Table 3. The EAWG Candidate Atmosphere Design Points

Pt. No.	Cabin Pressure, kPa (psia)	Cabin ppO2, kPa(psia)	Cabin Oxygen , volume %	EVA Suit Pressure, kPa (psia)	P(DCS)	General Characteristics
1	65 (9.4)	18.5(2.7)	28.5	29.6 (4.3)	0.089	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)	17.1(2.5)	26.8	29.6 (4.3)	0.094	Lowest cabin oxygen concentration with current space suit pressure; at hypoxic boundary.
3	73 (10.6)	16.9(2.5)	23.2	34.5 (5.0)	0.089	Moderate increase in space suit pressure with lower cabin oxygen concentration; at hypoxic boundary.
4	80 (11.6)	16.8(2.4)	21	41.4 (6.0)	0.038	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)	18.6(2.7)	21	41.4 (6.0)	0.089	Higher space suit pressure with Earth-normal cabin oxygen concentration; well above hypoxic boundary. Ground testing may be facilitated.
6	91.0 (13.2)	21.0(3.0)	23.1	41.4 (6.0)	0.089	Higher space suit pressure. Normoxic cabin atmosphere; slightly elevated oxygen concentration.
7	70.3 (10.2)	18.6(2.7)	26.5	29.6 (4.3)	0.178	Current space suit pressure. This point represents shuttle EVA preparation conditions.
8	65.5 (9.5)	19.7(2.9)	30	29.6 (4.3)	0.079	Current space suit pressure with assumed maximum oxygen concentration from the pressure study. O_2 concentration control limits are outside of existing materials flammability qualification envelope.
9	57.2 (8.3)	20.6(3.0)	36	29.6 (4.3)	0.011	Current space suit pressure. Highest oxygen concentration point (above that assumed in the pressure study) and lowest cabin pressure minimize prebreathe time. Outside of existing materials flammability qualification envelope.

Note: P(DCS) is the EAWG estimate of the probability of decompression sickness. The P(DCS) was computed for each design point given a 60-minute in-suit pre-breathe with an ambulatory subject performing a 40hour EVA that includes exercise (work) in addition to the ambulation to provide a worst-case prediction for a moon or Mars EVA.

Note: Oxygen concentrations in the table are nominal, and the upper control limits will be higher.



Notes: The Normoxic Equivalent and Hypoxic Boundary are taken from NASA-STD-3000 (NASA, 1995).
Lange's flammability limit is taken from Lange et al. (2005).
Oxygen concentrations in the figure are nominal, and the upper control limits will be higher.

Figure 2. The EAWG candidate atmosphere design space.

4.2 Study Process

A risk-based analytical process was performed by the EAWG that required that the group examine in detail the following risks as they relate to the design of spacecraft atmospheres:[*]

- Hypoxia: human performance degradation due to insufficient oxygen partial pressure available in the human lung.
- DCS: injury/illness due to the evolution of gas bubbles in human tissues after partial reduction of external pressure on the body.
- Fire: rapid, persistent oxidation of a material that releases heat, or heat and light, and is generally accompanied by flame.
- Mission impact: reduction in or loss of mission success due to human and/or system operational factors.

As the first effort in this analytical process, FTA was conducted to fully characterize these risks. The EAWG, working in its three subgroups, constructed fault tree models. These models were then encoded using FTA software by the analytical support team. The models link together multiple human, mission, system, and environmental conditions that form the basis of each risk. The models were validated by EAWG subgroup reviews. It was determined that many quantitative

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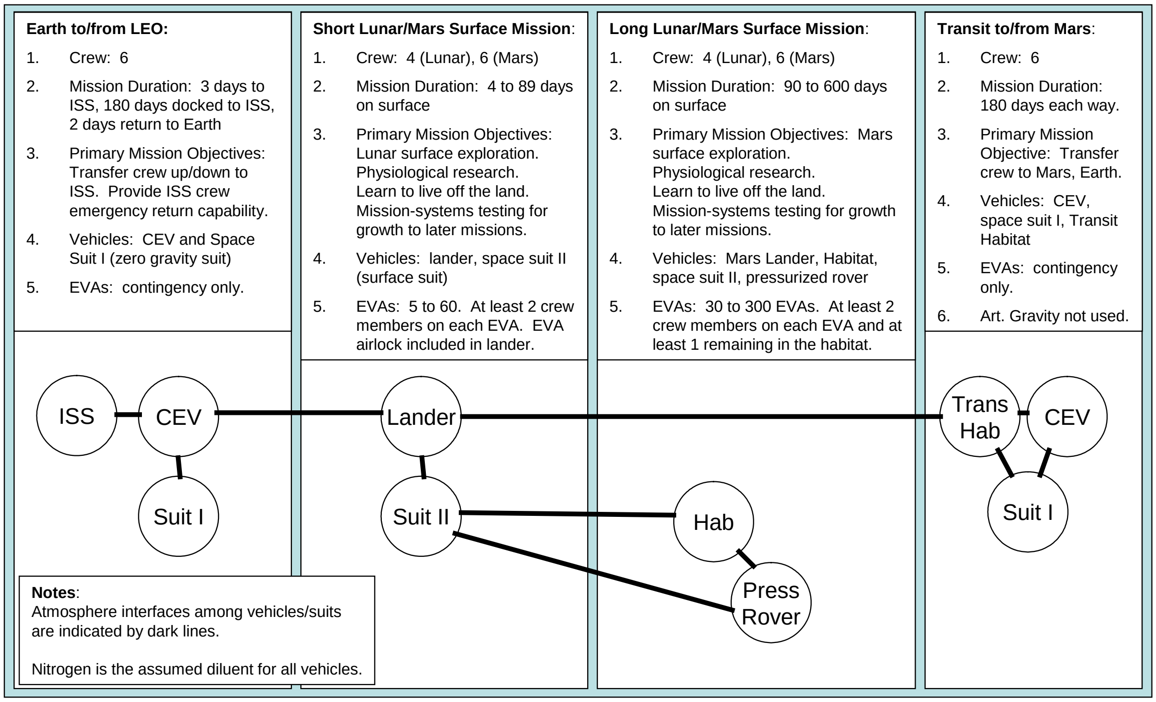
[*] These risks were used as the key figures of merit (FOMs) for evaluation of the candidate atmospheres.

data sets required to perform numerical calculations of risk magnitudes with these FTA models were not available to the EAWG. Therefore, the FTA analysis was concluded without calculating specific risk levels. Nevertheless the models, as constructed, are valuable as a starting point for future quantitative risk management by exploration programs and vehicle projects. Appendix C provides a report on the FTA effort performed by the EAWG.

The full ESAS was not available to the EAWG during the EAWG analysis cycle. A common set of mission-systems assumptions was generated by the EAWG to provide the necessary context for its analyses in the absence of the ESAS. When partial ESAS results became available late in the EAWG analysis cycle, the results were reviewed and compared to EAWG common assumptions; small differences were identified that did not cause a significant change in the EAWG approach or results. Figure 3 illustrates the EAWG mission-systems assumptions, as modified to match ESAS results that were available to the EAWG as of November 2005.



Earth to/from LEO:

1. Crew: 6
2. Mission Duration: 3 days to ISS, 180 days docked to ISS, 2 days return to Earth
3. Primary Mission Objectives: Transfer crew up/down to ISS. Provide ISS crew emergency return capability.
4. Vehicles: CEV and Space Suit I (zero gravity suit)
5. EVAs: contingency only.

Short Lunar/Mars Surface Mission:

1. Crew: 4 (Lunar), 6 (Mars)
2. Mission Duration: 4 to 89 days on surface
3. Primary Mission Objectives: Lunar surface exploration. Physiological research. Learn to live off the land. Mission-systems testing for growth to later missions.
4. Vehicles: lander, space suit II (surface suit)
5. EVAs: 5 to 60. At least 2 crew members on each EVA. EVA airlock included in lander.

Long Lunar/Mars Surface Mission:

1. Crew: 4 (Lunar), 6 (Mars)
2. Mission Duration: 90 to 600 days on surface
3. Primary Mission Objectives: Mars surface exploration. Physiological research. Learn to live off the land. Mission-systems testing for growth to later missions.
4. Vehicles: Mars Lander, Habitat, space suit II, pressurized rover
5. EVAs: 30 to 300 EVAs. At least 2 crew members on each EVA and at least 1 remaining in the habitat.

Transit to/from Mars:

1. Crew: 6
2. Mission Duration: 180 days each way.
3. Primary Mission Objective: Transfer crew to Mars, Earth.
4. Vehicles: CEV, space suit I, Transit Habitat
5. EVAs: contingency only.
6. Art. Gravity not used.

Notes:
Atmosphere interfaces among vehicles/suits are indicated by dark lines.

Nitrogen is the assumed diluent for all vehicles.

Figure 3. EAWG mission-systems assumptions.

The AHP was used as a tool to survey EAWG members to gather their expert opinion data on the nine candidate atmosphere design points. Each of the four FOMs was weighted, and each of the nine candidate atmospheres was ranked against these FOMs. The results were reviewed within the three EAWG subgroups at the August meeting. The AHP model of the results was used during this meeting to generate an EAWG cumulative ranking across all three discipline subgroups. This culminated in the weighted rankings illustrated in Table 4. The numbers in the cells of the table are the candidate atmosphere design points described in Table 3. The Phys/Med Ranking column is the ranking generated by that subgroup, based on hypoxia and DCS risks. The MissOps Ranking column was generated by experts in that subgroup, based on risk to mission operations; and the

Veh/Hab Ranking was generated by experts in that subgroup, based on fire risk. Appendix D contains a report on the AHP analysis and results.

Table 4. EAWG Expert Ranking of Candidate Atmospheres

Ranking Designator	Phys/Med Ranking	Miss Ops Ranking	Veh/Hab Ranking	AHP Weighted Ranking
1: Most Preferred	9	9	4	9
2	4	8	5	8
3	8	1	6	4
4	1	2	3	1
5	5	7	7	5
6	6	3	2	3
7	2	4	1	6
8	3	5	8	2
9: Least Preferred	7	6	9	7

Note: Numbers in cells are the candidate atmosphere design points described in Table 3.

To further analyze and detail significant findings and issues related to atmosphere design, EAWG members generated white papers on several topics; these are listed in Table 5. The papers, which were made available prior to the workshop to give outside reviewers a deeper understanding of the various issues being addressed by the EAWG ,are included in Appendix E..

Table 5. EAWG White Paper Topics

Number	Topic
1	Ambulation During EA on Moon and Mars as a Risk Factor for DCS
2	Variable-Pressure EVA Surface Suit
3	Aspects of Oxygen Partial Pressure, Diluents, and Gravity on Atmosphere Selection for Constellation Systems
4	The Effect of Long-Term Partial Pressure Oxygen Exposure
5	Materials Flammability Control for Constellation Program: Impacts for Enriched Oxygen Environments
6	Space Radiation Shielding Materials

Analysis of the white papers resulted in the following summary of significant findings:

- Ambulation Effects on DCS
    - Based on ground test subject evaluations with otherwise equivalent EVA conditions, DCS risk may be significantly higher traversing planetary surfaces than experienced on shuttle and ISS.
    - Eliminating DCS risk takes on added importance for a multi-EVA surface scenario.
    - Significant uncertainty exists concerning how the "lunar loping" gait seen in Apollo missions compares with ambulation under ground test conditions.

- Variable Pressure/Multi-Pressure EVA Suit
    - A multi-pressure suit appears achievable.
    - Such a suit has a higher programmatic risk that requires engineering to minimize mass and achieve required reliability for surface EVAs.
    - Nevertheless, a multi-pressure suit presents distinct advantages for planetary EVA operations and DCS risk mitigation.

- Flammability of Materials
    - A 36% oxygen content cabin atmosphere is supportable with current materials technologies.
    - Engineering development will be needed, however, including additional materials testing (additional program cost).
    - There may be added operational restrictions related to items such as crew clothing.

Quantitative breakpoints for analysis also were identified as follows:

- 30% oxygen is the maximum flammability test level for ISS/Space Shuttle Programs;
- 70% and 100% oxygen were used operationally by past human programs;
- a 1-hr pre-breathe is a reasonable maximum time for operations and physiology;
- a 3.5-pounds per square inch, absolute (psia) suit pressure is a reasonable minimum based on physiology; and
- a 6-psia suit pressure is a reasonable operating maximum based on engineering capability.

Gap analysis was also performed by the EAWG. Actions taken at the EAWG August meeting included providing a definition of research and technology needs related to atmosphere selection as well as their impacts on humans, vehicles, and spacesuits. White papers included additional information on these areas of needs and their engineering challenges, all of which were then captured in the gap analysis.

After the EAWG conducted the analytical processes described above, the group synthesized a tenth candidate atmosphere design point to use as a reference design at its workshop to ensure that outside reviewers could direct their comments toward a specific point in the trade space. It was understood that this reference design was not the final recommendation of the EAWG and that it was open to change based on workshop results. Figure 4 illustrates this reference design, designated Point X, which was designated as a control box centered on 8.5 psia and 32% oxygen.

This vehicle atmosphere concept enabled an option of a variable-pressure spacesuit initially operated at 6 psia to eliminate DCS risk during nominal EVA depressurization. This suit could then be lowered to 4 psia for dexterous EVA tasks.

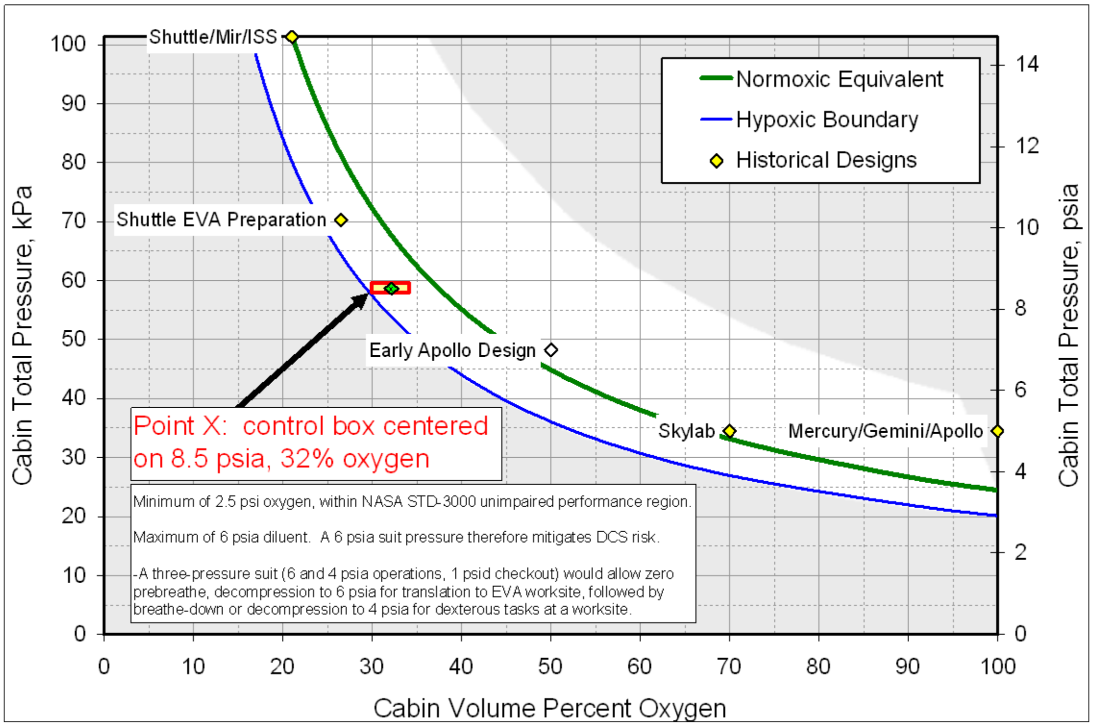


Figure 4. Workshop reference design Point X.

The Exploration Atmospheres Workshop was held November 1-3, 2005 in Houston, the report is of which is included as Appendix F. Inputs from reviewers at the workshop provided new data or citations in several areas related to human physiology, including recent data on U.S. Air Force studies of hypoxia (Balldin et al., 2005).

Based on the outcome of the workshop and EAWG deliberations, technical gaps relevant to atmosphere design were tabulated. Information on these gaps is included here for information and consideration but is not considered exhaustive or prioritized. Table 6 lists human research areas, Table 7 itemizes technology development areas, Table 8 cites the engineering challenges, and Table 9 catalogs expected programmatic impacts and opportunities for Constellation. Note that several items in Table 6 are already in the Bioastronautics Roadmap (NASA, 2005) as part of the NASA human research agenda for exploration risk mitigation.

After its workshop discussions and findings, the EAWG conducted additional analysis and reached consensus on a draft set of recommendations for vehicle and spacesuit atmospheres. These are documented in Section 5 of this report.

Table 6. Human Research Areas

Research Question
What is the probability of DCS as a function of tissue ratio under microgravity, moon partial gravity, and Mars partial gravity?
What is the most effective pre-EVA DCS prevention strategy to include pre-breathe with various gases, exercise, and other medical measures?
What are the best treatment strategies to manage ebulism?
What are the most effective, yet safe and energy- and space-efficient, means of managing DCS in the space flight milieu, including the use of hyperbaric oxygen delivery and other promising technologies; and how might they be adapted for reduced-G operations?
What is the risk of DCS after an acute environmental insult – eg, leaking module or damaged EMU – and what treatment or response options are available under these off-nominal situations?
What are the operational and medical impacts of off-nominal performance of DCS countermeasures?
What are the risk factors that can increase the likelihood of DCS, such as the presence of patent foramen ovale (PFO)?
Is it possible to perform interplanetary EVA; and what are the DCS risk mitigation options for interplanetary EVA (eg, moon and Mars) given that a tri-gas breathing mixture including argon is present?
What burn treatment (external and inhalation) should be used in reduced gravity?

Table 7. Vehicle Research and Technology Development Areas

Need
Effects of pressure, gravity, oxygen mole fraction, and diluent gas on material flammability.
Acceptable materials for clothing, windows, stowage foam, and radiation protection for oxygen % above 30%.
Detection of fires in alternate environments and atmospheres must be evaluated..
Development of fire suppression systems that are effective for oxygen concentrations > 30% (“No good story for putting out fires”).
Methodology for maintaining configurations controls over long duration.
Development of nonflammable coverings and coatings for flammable materials.
Methodology to assess total risk of fire to vehicle/habitat system.
Food processing: Development of an EMI [electromagnetic interference]-acceptable microwave oven.
Develop understanding of ignition mechanisms for high oxygen concentration systems (flow friction and particle impact).
Effect of atmospheric noise and voice communications.
Effect of low-atmosphere pressure on food preparation and processing.
Threshold for flammability of hair and skin.
Material flammability during medical operations.

Table 8. Engineering Challenges

Challenge
How do the different oxygen % and pressure combinations change leakage risks in cabins/habitats?
Variable-pressure suit: added complexity, weight, and increased loads certification.
Variable-pressure suit: motorized regulator will most likely be heavier, bulkier, more costly, and susceptible to more failure modes.
Variable-pressure suit: the impacts on DCS risk in an emergency situation (suit pressure of 3.3 to 3.9 psia) with an initial higher suit pressure (6 to 8 psia) need to be considered; or an emergency pressurization system with variable set point could be developed that “follows” the primary regulator set-point changes (see regulator challenge).
Variable-pressure suit: relief valve to enable quick reduction of suit pressure to desired operating range function would be more difficult to implement in a variable-pressure suit as the final set points are unknown.
Variable-pressure suit: ventilation fan designed to operate at variable pressures will probably not be as efficient as a fan finely tuned to work at one specific pressure.
Variable-pressure suit: advanced microphones to work in a variable pressure environment.
Variable-pressure suit: vent loop sensors to operate in a variable-pressure environment (eg, carbon dioxide [CO_2] sensor).

Challenge
Variable-pressure suit: swing-bed scrubber to operate in variable pressure (assuming technology becomes available).
Variable-pressure suit: power efficiency for technologies designed for a specific pressure range will decrease as well as the fidelity of the subsystem.
Variable-pressure suit: increased loads, increased weight, and reduced operating life of the pressure garment.
Variable-pressure suit: soft components subjected to loads greater then 6.0 psi repeatedly may need redesign to hard composite components to maintain a longer cycle life. Also, hard goods provide less adjustability (add parts mass), are more expensive to design and manufacture, and require more stowage volume.
Variable-pressure suit: glove dexterity will be decreased. Some soft components of the gloves could have to be switched to hard components.
Materials flammability: composites and polymers proposed for space radiation control might have to be wrapped in nonflammable material.
Materials flammability: polycarbonates (transparent window materials) may be lost at 30% or greater nominal oxygen concentrations.
Materials flammability: lack of materials choices affects cost.
Materials flammability: fluoropolymer coatings have been used on flammable commercial off-the-shelf (COTS) items for shuttle and ISS. Such coatings may not work at higher oxygen concentrations and are fragile.
Radiation shielding: most effective shields are materials rich in hydrogen and carbon, which tend to be flammable. Polyethylene will have to be coated with nonflammable material for use as an internal radiation shield or structural material.

Table 9. Programmatic Impacts

Impact
Variable-pressure suit: With the design implications required to achieve a variable-pressure suit, there is additional program risk (cost, schedule, and technical) over current single/dual-pressure suit design.
Variable-pressure suit: additional formal studies needed within the EVA program to further assess the potential issues associated with a variable-pressure suit concept.
Variable-pressure suit (opportunity): substantial long-term benefits over a single- (or dual-) pressure suit to adapt to changing requirements or unforeseen operational hurdles.
Partial-pressure oxygen exposure: “Once cabin pressure has been selected, decompression studies with human subjects will be necessary to develop pre-breathe protocols that control risk of DCS to acceptable levels.”
Materials flammability: Cost increases due to restricted use of commercial off-the-shelf equipment items at enriched oxygen levels.

5 Recommendations for Mission Systems Design

This section captures major technical findings and recommendations resulting from the EAWG trade study and closely related efforts. These recommendations are directed toward exploration programs within the agency, and specifically toward the Constellation Program. Section 6.0 also provides recommendations on future NASA work related to atmosphere design and selection. The recommendations provided herein are not requirements; they reflect technical considerations only.

5.1 Agency and Constellation Program Level

The Constellation Program should plan for a well-integrated design extending across all vehicle atmospheres to ensure crew safety, vehicle reliability, mission design flexibility, systems inter-operability, and crew operational efficiency.

As detailed in Table 10, the initial CEV, designated to provide crew transfers to the ISS, and the lunar and Mars CEVs should use atmospheres consistent with current agency technical standards and with current program design and operational experience. CEV internal total pressures of 14.7 and 10.2 psia (nominal) meet these criteria. The CEV must also support a vacuum atmosphere to accommodate contingency EVA.

Table 10. Summary of Recommendations for Constellation Mission Systems

Vehicle	Nominal Total Pressure (psia ± 0.2 psia)[4]	Nominal Oxygen Partial Pressure (mmHg)[4]	Nominal Oxygen Concentration (% ± 2.0 percentage points)[4]	Range of Total Pressure Capability (psia)[1]	Tissue Ratio (R) After 60 Minutes Pre-breathing[3]
CEV to ISS	14.7 10.2[5]	160 (0 ft) 140 (3500 ft)	21 26.5	0-14.9	
CEV In-Space Suit	4.3	222	100	4.0-4.6	1.55 from 10.2 psia CEV to 4.3-psia suit
Lunar and Mars CEV	14.7 10.2	160 (0 ft) 140 (3500 ft)	21 26.5	0-14.9	
Lunar and Mars Landers	10.2 8.0	140 (3500 ft) 132 (5000 ft)	26.5 32	0-14.9	
Lunar and Mars Surface Suits	4.3 6.0	222 310	100 100	3.5-8.0 [2]	1.13 from 8.0 psia landers to 4.3-psia suit; 1.07 from 7.6 psia surface habitats to 4.3-psia suit
Lunar and Mars Surface Habitats	8.0 7.6	132 (5000 ft) 126 (6500 ft)	32 32	0-14.9	
Mars Transit	14.7 10.2	160 (0 ft) 140 (3500 ft)	21 26.5	0-14.9	

Note 1: Range of total pressure capability covers Earth launch, Earth entry, and contingencies.

Note 2: Surface suit 3.5-psia capability for suit emergency operations, 8.0 psia for DCS treatment.

Note 3: Sixty minutes in-suit pre-breathe is defined as the time in the suit after purge and leak check until absolute pressure on the body reaches 4.3 psia after a nominal depressurization. Nitrogen is the assumed diluent gas.

Note 4: All nominal values are centers of control boxes assumed ±0.2 psia total pressure, ±2 percentage points oxygen.

Note 5: The 10.2-psia recommendation for CEV contingency EVA preparation is based on shuttle experience.

The lunar and Mars landers should provide atmospheres that enable docking with the CEV and support-efficient surface EVA preparation and high-EVA frequency for surface sortie missions. Atmospheres of 10.2 and 8.0 psia (nominal) internal pressure meet these requirements.

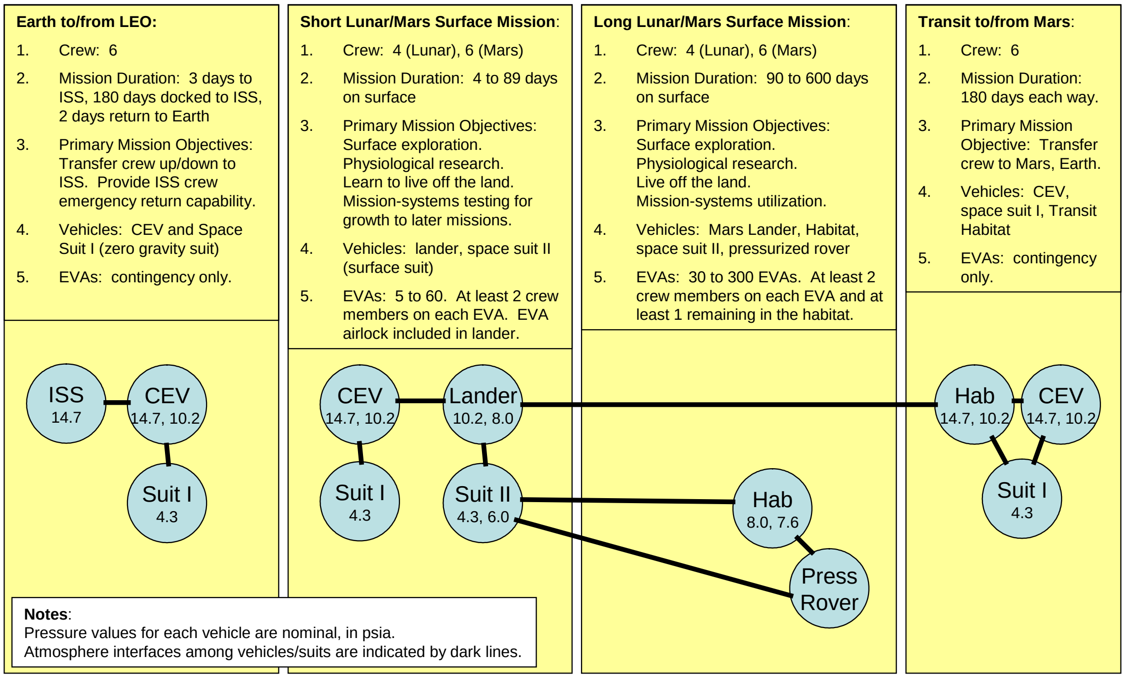
The lunar and Mars surface habitat elements should use atmospheres of 8.0 and 7.6 psia (nominal). After extended acclimation of surface habitat crew members, the lower pressure can be used, further enhancing efficient and frequent EVA capabilities.

The in-space suit for contingency EVA should provide an internal atmosphere of 4.3 psia (nominal). The surface spacesuit used for planned EVA should provide internal atmospheres of 4.3 and 6.0 psia (nominal). The 6.0-psia atmosphere is useful to enable rapid EVA egress, with minimum DCS risk, from the lander and surface habitat. The 4.3-psia atmosphere is useful for dexterous EVA task performance.

It is noted that several of these recommended atmospheres may result in conditions slightly outside current agency hypoxia standards, as documented in NASA-STD-3000, figure 5.1.2-2 (NASA, 1995). These recommendations are based on the most recent, substantial physiological testing evidence, which states that healthy individuals can perform reliably under recommended conditions, including equivalent altitudes up to 8000 ft (118 mmHg oxygen pressure) without prior acclimation and up to 10 000 feet (110 mmHg oxygen pressure) with an extended period of acclimation (Balldin et al., 2005; Waligora et al., 1982).

Note also that several of the recommended atmospheres involve oxygen volume concentrations slightly greater than 30%, which is the maximum nonmetallic materials flammability certification level used by current operational human space flight programs.

Table 10 provides a summary of the recommendations to Constellation. Figure 5 illustrates how they relate to and integrate with each other. Figure 6 illustrates the recommended atmospheres in the context of historical NASA spacecraft designs.



Earth to/from LEO:

1. Crew: 6
2. Mission Duration: 3 days to ISS, 180 days docked to ISS, 2 days return to Earth
3. Primary Mission Objectives: Transfer crew up/down to ISS. Provide ISS crew emergency return capability.
4. Vehicles: CEV and Space Suit I (zero gravity suit)
5. EVAs: contingency only.

Short Lunar/Mars Surface Mission:

1. Crew: 4 (Lunar), 6 (Mars)
2. Mission Duration: 4 to 89 days on surface
3. Primary Mission Objectives: Surface exploration. Physiological research. Learn to live off the land. Mission-systems testing for growth to later missions.
4. Vehicles: lander, space suit II (surface suit)
5. EVAs: 5 to 60. At least 2 crew members on each EVA. EVA airlock included in lander.

Long Lunar/Mars Surface Mission:

1. Crew: 4 (Lunar), 6 (Mars)
2. Mission Duration: 90 to 600 days on surface
3. Primary Mission Objectives: Surface exploration. Physiological research. Live off the land. Mission-systems utilization.
4. Vehicles: Mars Lander, Habitat, space suit II, pressurized rover
5. EVAs: 30 to 300 EVAs. At least 2 crew members on each EVA and at least 1 remaining in the habitat.

Transit to/from Mars:

1. Crew: 6
2. Mission Duration: 180 days each way.
3. Primary Mission Objective: Transfer crew to Mars, Earth.
4. Vehicles: CEV, space suit I, Transit Habitat
5. EVAs: contingency only.

Notes:
Pressure values for each vehicle are nominal, in psia.
Atmosphere interfaces among vehicles/suits are indicated by dark lines.

Figure 5. Integrated atmosphere recommendations for Constellation.

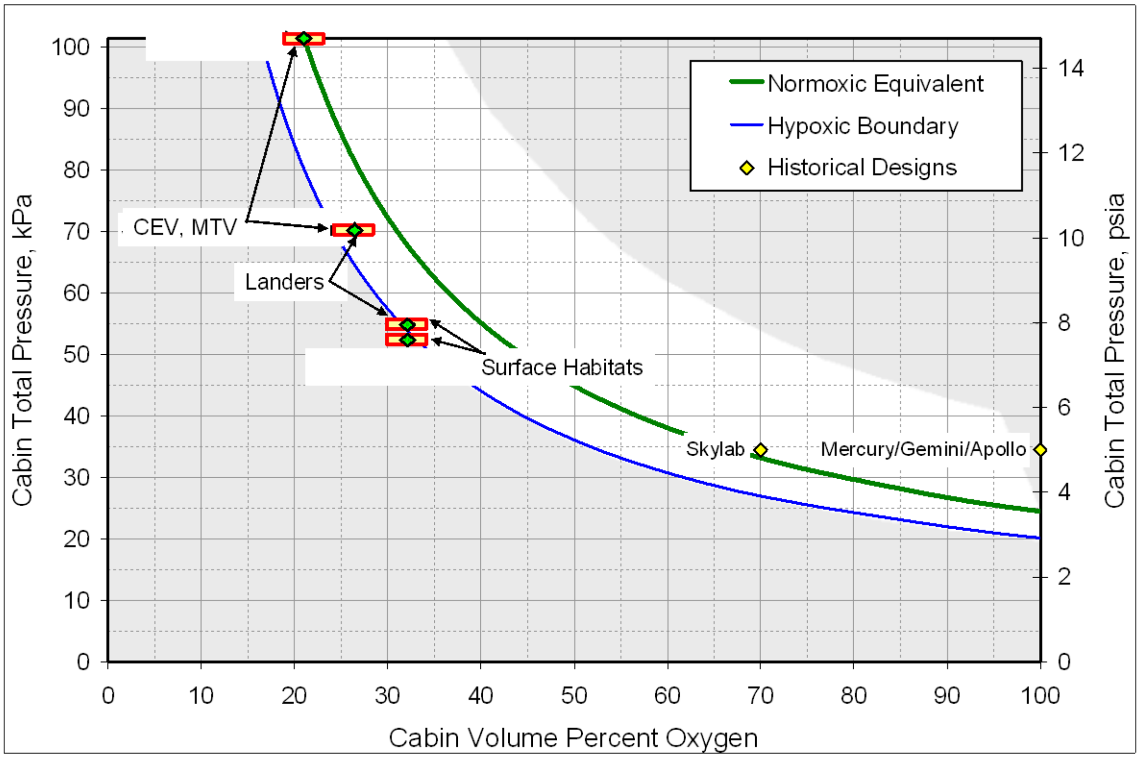


Figure 6. Historical spacecraft and recommended Constellation atmospheres.

Each vehicle cabin mixed-gas atmosphere is assumed to be controlled within a range of total pressures and oxygen partial pressures, resulting in a notional control box, as depicted in figure 7. The nominal total pressures, oxygen partial pressures, and oxygen concentrations given in Table 10 are at the center of each control box. It was assumed by the EAWG that the control box for each vehicle atmosphere is ±0.2 psia on the total pressure axis and ±percentage points on the oxygen concentration axis. When actual control boxes are generated later in each vehicle design cycle, they may vary from these assumptions.

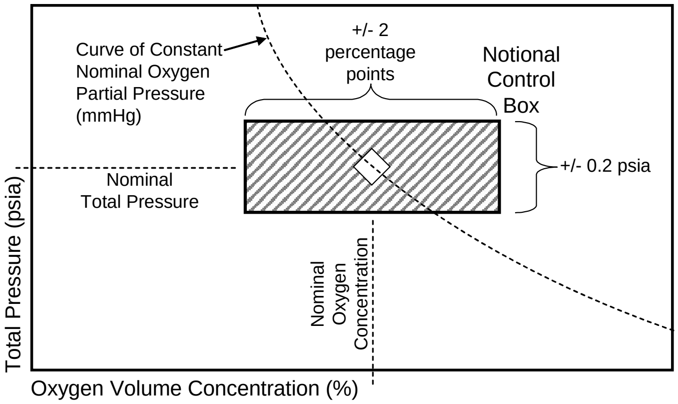


Figure 7. Notional control box for vehicle cabin atmospheres.

Note that, using this notional control box, the 10.2 psia, 26% oxygen atmosphere implies a maximum oxygen concentration of 28.5%. However, the EAWG assumes that, in this case, Constellation will make use of the fact that the Space Shuttle and ISS Programs have certified many materials for use at a maximum of 30% oxygen.

5.2 Crew Exploration Vehicle to International Space Station

The initial CEV mission is intended to service the ISS with crew and cargo. Compatibility with the nominal ISS atmosphere of 14.7 psia and 21% oxygen as well as the rapid development cycle for the initial CEV place heavy emphasis on the use of existing technology and flight operations techniques.

Current space shuttle atmosphere designs and attendant capabilities were considered by the EAWG to meet the needs of this CEV mission. Per Table 10, the CEV to ISS is recommended to use a 14.7 psia, 21% oxygen atmosphere for normal operations and a 10.2 psia, 26.5% oxygen atmosphere for contingency EVA preparation when undocked from ISS. These atmospheres fit within both agency health standards and current system design regimes; they also allow the use of existing COTS hardware, clothing, stowage containers, etc. that are certified for flammability to Shuttle/ISS requirements.

5.3 Crew Exploration Vehicle In-Space Suit

The CEV in-space suit is assumed to provide only contingency EVA capability in low-Earth Orbit (LEO), as well as during transit to and from the moon and Mars. The rapid development cycle for this suit places heavy emphasis on the use of existing technology and flight operations techniques.

Current EVA Portable Life Support System (PLSS) atmosphere designs and attendant capabilities were considered by the EAWG to meet the needs of this suit. Per Table 10, the in-space suit is recommended to use a normal operations atmosphere of 4.3 psia oxygen. This atmosphere fits within agency health standards and current materials flammability test regimes.

5.4 Lunar and Mars Crew Exploration Vehicle

The CEV is also intended to function in both lunar and Mars crew transit missions. This CEV must interface with both lunar and Mars vehicles, including the lunar lander and the Mars transit vehicle. Per Table 10, the lunar and Mars CEVs are recommended to use atmospheres like those of the ISS CEV.

5.5 Lunar and Mars Landers

The lunar lander is intended to deliver crew and cargo to and from the lunar surface. The Mars lander is assumed to perform a similar function for access to the martian surface. On the planetary surfaces, these landers support multiple EVA excursions during short-duration surface stays. These landers must interface with both lunar and Mars vehicles, including the lunar CEV, the Mars transit vehicle, and the surface suits.

The available development schedule for these vehicles allows the use of new technology and flight operations techniques. New atmosphere designs and attendant capabilities were considered by the EAWG to best meet the needs of these lander missions. Per Table 10, the lunar and Mars landers are recommended to use both a 10.2-psia atmosphere for docked operations with the CEV and an 8.0-psia atmosphere for planetary surface operations. The 8.0-psia atmosphere design extends slightly beyond current agency health standards and current materials flammability test regimes.

Exposed nonmetallic materials for the landers will have to be evaluated for flammability in the higher maximum oxygen concentration proposed for their missions. The impact to materials selection is not expected to be large, given that most exposed surfaces of vehicle hardware will be metal or painted metal and standard aerospace electrical wiring, all of which are known to meet flammability requirements at oxygen concentrations well beyond those proposed for the lunar and Mars missions. However, flammability in the increased oxygen concentration could be a design driver for composites used in the internal structure.

It is especially important to note that these recommendations for landers must be examined more closely prior to development of requirements for the vehicles.

5.6 Lunar and Mars Surface Suits

The surface suit is intended to provide for a multiple, low-overhead EVA capability on the planetary surface. The available development schedule for this suit emphasizes the use of new technology and operations techniques to achieve EVA objectives. The surface suits interface with lunar and Mars landers and surface habitats.

The current EVA PLSS nominal operations atmosphere design (4.3 psia) was considered by the EAWG to meet the dexterous task needs of these surface suits. Per Table 10, the lunar and Mars surface suits are recommended to use atmospheres of 4.3 and 6.0 psia, respectively, to provide flexibility in EVA preparation and operations. The 6.0-psia atmosphere is useful to enable rapid EVA egress, with minimum DCS risk, from the lander and the surface habitat. The 4.3-psia atmosphere is useful for dexterous EVA task performance.

An additional optional atmosphere of 8.0 psia is recommended as an in-suit treatment capability for DCS. A 3.5-psia capability is also recommended for certain EVA system contingencies.

5.7 Lunar and Mars Habitats

The lunar habitat is intended to provide for long-duration crew habitation and EVA access on the lunar surface. The Mars habitat performs a similar function on the martian surface. While these habitats interface with the surface suits to support multiple EVA excursions during long-duration surface stays, they may interface with pressurized rovers or other similar surface systems pressurized elements.

The available development schedule for these habitats allows the use of new technology and flight operations techniques. New atmosphere designs and attendant capabilities were considered by the EAWG to best meet the needs of these habitat missions. Per Table 10, the lunar and Mars habitats are recommended to use both 8.0- and 7.6-psia atmospheres for normal operations. After an extended period of 8.0-psia operations, the crew can acclimate to the 7.6-psia pressure, which provides even greater EVA preparation and egress efficiency. These atmosphere designs extend slightly beyond current agency health standards and current materials flammability test regimes.

It is especially important to note that these recommendations for surface habitats must be examined more closely prior to developing requirements for those elements.

5.8 Mars Transit Vehicle

The Mars transit vehicle is intended to provide for long-duration crew habitation during transit to Mars as well as during the return transit to Earth. This vehicle was assumed to interface with the in-space suit, the Mars CEV, and the Mars lander.

Per Table 10, the Mars transit vehicle is recommended to initially operate at 14.7- and 10.2-psia atmospheres. The total pressure can be decreased to 10.2 psia during transit to Mars, thus achieving a degree of crew acclimation prior to Mars arrival for surface operations at 8.0 and 7.6 psia.

6 Exploration Atmospheres Working Group Recommendations for Future Work

The EAWG was not intended to provide the ultimate, conclusive point design for all spacecraft atmospheres because many decision-making factors are inherently programmatic in nature, including cost and schedule issues and impacts. Therefore, recommendations are given below for specific NASA programs to perform further work that will leverage the EAWG technical results for Constellation mission-systems design and implementation.

6.1 Human Research Program

The EAWG recommends that the Human Research Program consider researching the areas listed in Table 6. This research would support the Office of the Chief Health and Medical Officer (OCHMO) in developing agency-level human health, medical, and environmental standards and Constellation in developing lunar and Mars mission capabilities. It is noted that several similar research questions are currently in the Bioastronautics Roadmap (NASA, 2005).

It is also recommended that the OCHMO, supported by the exploration medicine team, consider updating the hypoxia standards to allow the Constellation Program to design to the levels of atmospheric oxygen associated with the EAWG recommendations in Section 5.0.

6.2 Technology Development Program

The EAWG recommends that the ESMD Technology Development Program consider research and technology development in the areas listed in Table 7 to support the Constellation Program in developing lunar and Mars missions.

6.3 Constellation Program

The EAWG recommends that the Constellation Program perform program-specific trade studies to evaluate the atmosphere recommendations in this report to generate atmosphere requirements for Constellation vehicles and suits. These studies should account for program factors that the EAWG did not analyze. These may include many program advantages and disadvantages, such as cost impacts per year for gas leakage, EVA pre-breathe time, and the nonmetallic materials development/test/certification/usage control process.

The EAWG recommends that the Constellation Program perform systems engineering to address the areas listed in Table 8. The EAWG also recommends that the Constellation Program study the issues and potential programmatic impacts (eg, cost, schedule, definition of acceptable risk) listed in Table 9.

Because of the uncertainties in the final maximum oxygen percentage concentration to be used, Constellation should modify the standard NASA flammability test as soon as possible to generate ignition threshold and material flammability data for key spacecraft materials over the range of conditions identified in this report. The modified test will allow NASA to identify materials at risk from possible increases in oxygen concentration and minimize potential impacts.

It is recommended that, in future testing, the NASA groups involved in materials flammability testing begin to plan for certification testing at increased oxygen concentration levels.

6.4 Crew Exploration Vehicle Project

The EAWG recommends that the CEV Project support the atmosphere trade study described in Section 6.3. CEV should also incorporate findings from the Human Research Program, the Technology Development Program, Constellation, and the Exploration EVA team into its vehicle atmosphere design to support lunar and Mars missions.

6.5 Advanced Projects

The EAWG recommends that Constellation Advanced Projects support the trade study described in Section 6.3 from an EVA and future habitable elements standpoint. For example, a comprehensive trade study to evaluate acceptable materials at the elevated oxygen levels recommended for both landers and surface habitats must be conducted to ensure that technical and programmatic considerations are assessed.

The Exploration EVA team should also incorporate findings from the Human Research Program, the Technology Development Program, Constellation systems engineering, and the CEV Project into its suit atmosphere design to support lunar and Mars missions.

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Appendix A:

Exploration Atmospheres Working Group Members

Barghouty, Nasser	Code XD41, NASA MSFC
Buderer, Melvin	Code SK, NASA JSC
Campbell, Paul	Lockheed Martin Space Operations
Chambliss, Joe	Code EC1, NASA JSC
Conkin, Johnny	Code SK, NASA JSC
Drake, Bret	Code EX, NASA JSC
Ewert, Michael	Code EC2, NASA JSC
Fitzpatrick, Daniel	Code SD37, NASA JSC
Galbreath, Gregory	Code ES2, NASA JSC
Gernhardt, Michael	Code CB, NASA JSC
Henninger, Donald	Code EC1, NASA JSC
Jones, Jeff	Code SD, NASA JSC
Khan-Mayberry, Noreen	Code SF23, NASA JSC
Lange, Kevin	Jacobs Sverdrup Technology
Lawson, Michael	Code EC1, NASA JSC
Lin, Chin	Code EC2, NASA JSC
McCandless, Jeff	NASA HQ, NASA ARC
Morin, Lee	Code CB, NASA JSC
Patrick, Jeff	Code XA, NASA JSC
Pedley, Michael	Code ES4, NASA JSC
Perchonok, Michele	Code SF3, NASA JSC
Powell, Michael	Code SK, NASA JSC
Ruff, Gary	Code PTO0, NASA GRC
Rust, Randy	Code NX, NASA JSC
Severance, Barbara	Code DF, NASA JSC
Trevino, Robert	Code EC5, NASA JSC
Urban, David	Code RUC0, NASA GRC
Waligora, Jim	USRA

Appendix B:

Exploration Atmospheres Working Group Implementation Plan

This is a product of the Crew and Thermal Systems Division (CTSD), Engineering Directorate, Johnson Space Center. The chair or lead for this activity is Don Henninger, Chief Scientist for CTSD and Paul Campbell of Space Life Sciences is Deputy. Support for the development of this document was provided by the Human Systems Research and Technology Theme Systems.

1.0 BACKGROUND

As NASA plans human exploration missions and develops new spacecraft and habitats, it must specify environmental requirements for the human-occupied systems. One such requirement is the definition of the human habitation atmosphere – pressure and constituent gases. Human-occupied spacecraft and habitat environments must provide a safe atmosphere. Total atmospheric pressure and constituent gas composition must be consistent with human physiology, the space environment, the spacecraft or habitat design, and with space exploration mission objectives.

NASA's currently operating human spacecraft, the Shuttle and the International Space Station (ISS), nominally operate at 101 kPa (14.7 psi). An exception is that prior to an Extravehicular Activity (EVA), Shuttle atmospheric pressure is lowered to 70 kPa (10.15 psi) to reduce pre-breathe times for the EVA in suits where the pressure is 30 kPa (4.3 psi) (see Figure 1). In the case of the ISS, an airlock is used for egress and ingress during EVA events. Now that NASA is preparing to design and build new spacecraft and habitats, it is prudent to assess the optimum design space parameters for the human habitable atmospheres (spacecraft cabins, planetary surface habitats, airlocks, spacesuits, and pressurized rovers). Preliminary design bounds have been added to facilitate the discussion (see Figure 1).

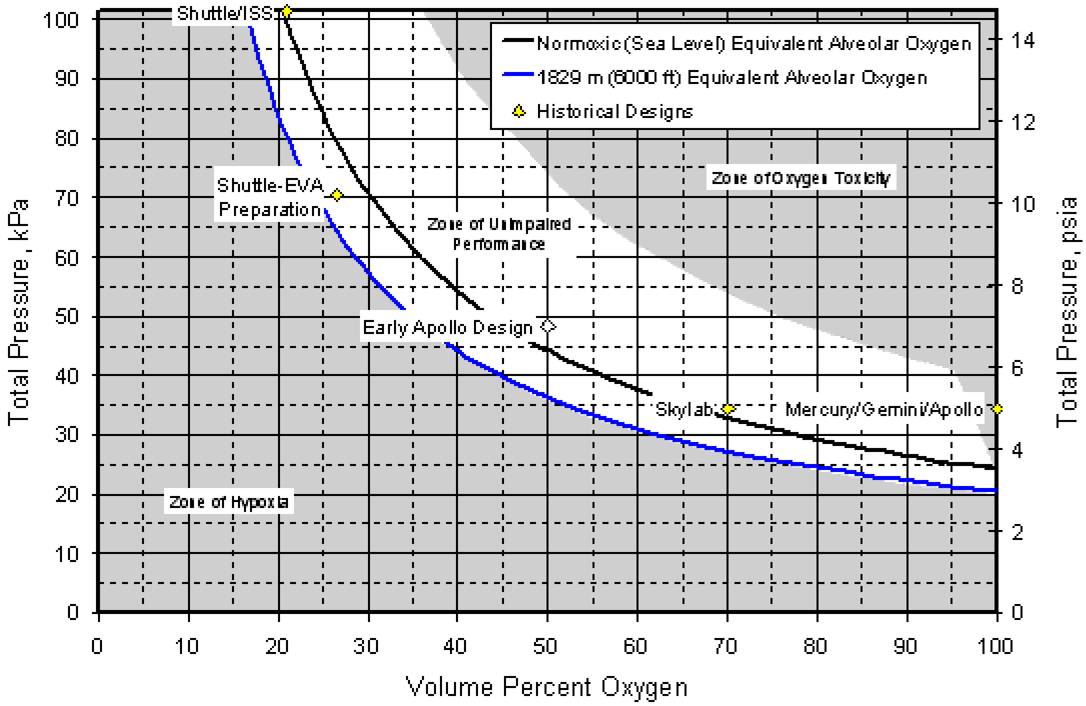


Figure 1. Assumed design bounds based on respiration requirements. Historical spacecraft cabin atmosphere conditions are shown for comparison.

2.0 OBJECTIVES AND ANTICIPATED RESULTS

The objective of this task is to refine the atmospheric design space to a relatively small domain such that atmospheric requirements for space-based systems can be specified.

3.0 APPROACH AND PRODUCTS

An Exploration Atmospheres Working Group (EAWG) will be formed consisting of technical and programmatic stakeholders to evaluate current knowledge and define the viable design space domain. A general process is shown in Figure 1. The EAWG will conduct additional analyses to further refine the design space domain. After reaching a consensus on the design space domain, a workshop will be convened to review these results and solicit additional inputs. The EAWG will then make recommendations for additional research and technology development to enable NASA to specify exploration atmosphere requirements. The EAWG will support development of requirements and integration into the Exploration Systems Mission Directorate (ESMD) Constellation Systems documentation.

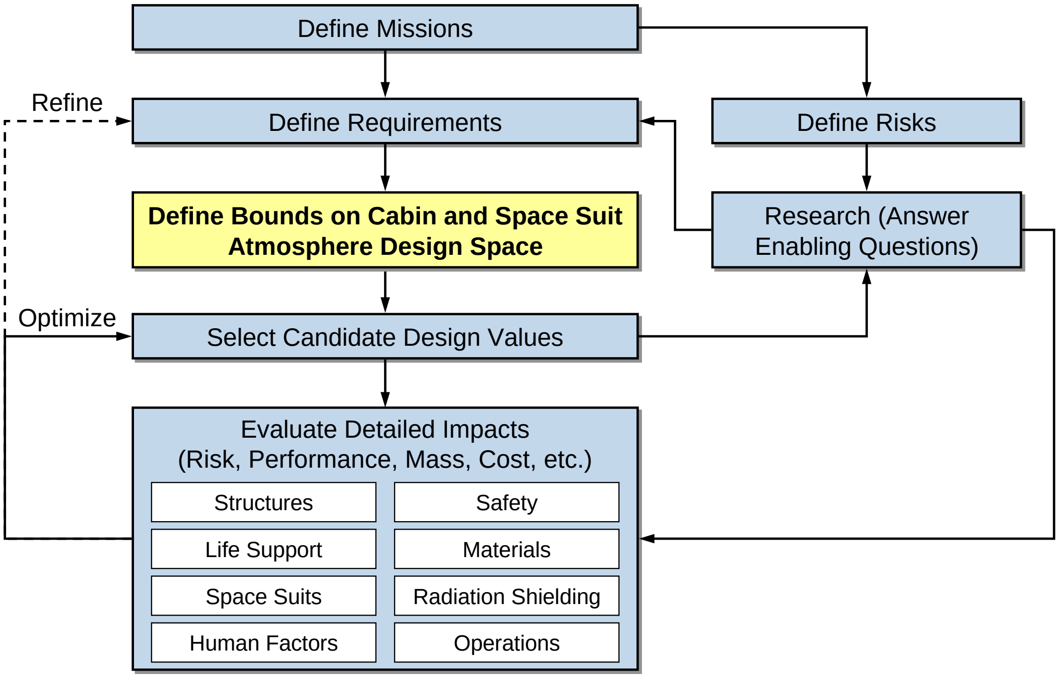


Figure 2. Envisioned atmosphere selection process.

The EAWG will determine the technical analysis approach and process(s) to be used to arrive at its recommendations on atmospheric pressure and composition. A straw man technical approach to be considered is quantitative risk analysis (see Figure 2), to ensure that the recommended atmosphere(s) control all risks to exploration crews and missions.

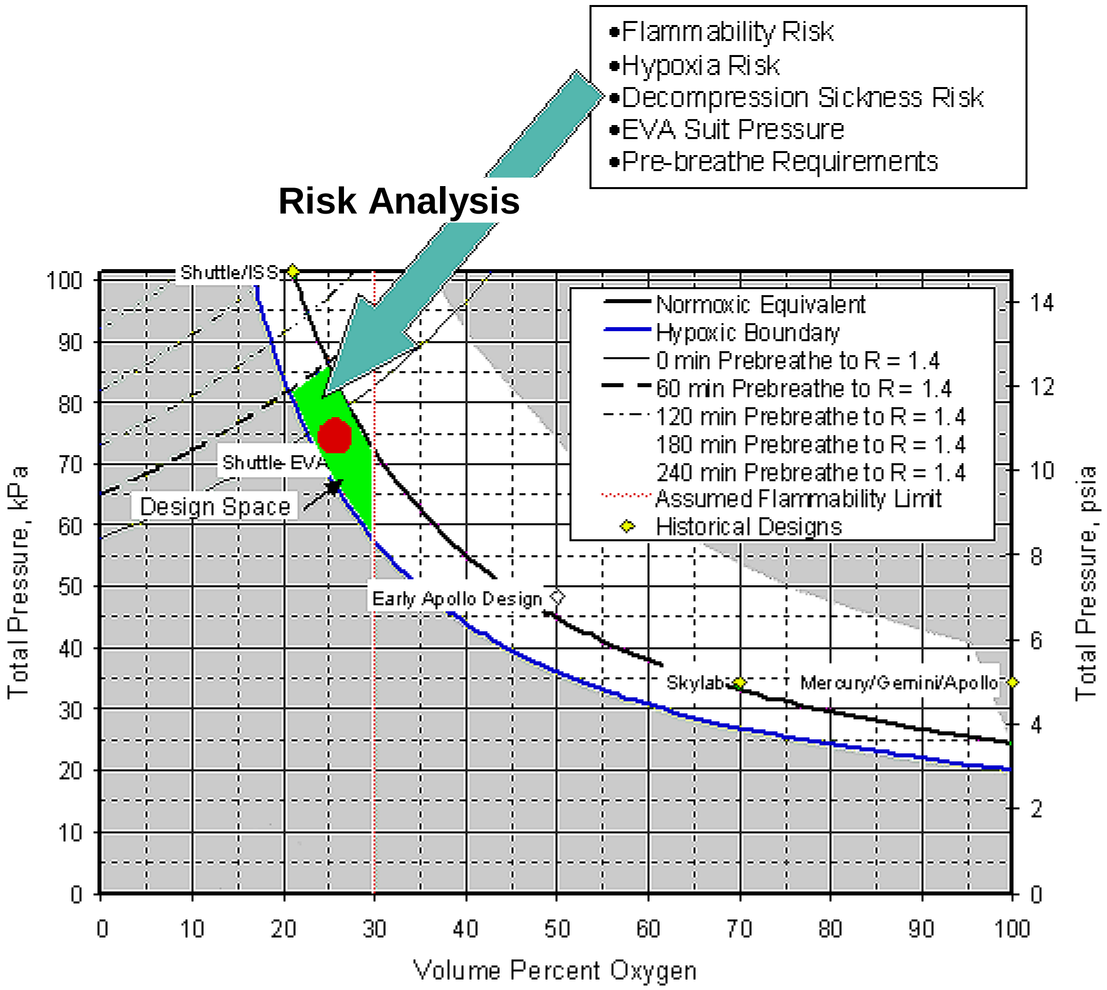


Figure 3. Notional risk-based process for definition of habitat and suit atmosphere requirements.

Form EAWG: May 2005

Identified technical and programmatic stakeholders or designees will be invited by the EAWG chair to review and discuss the topic. Competing positions relative to future human exploration missions will be identified and documented. The EAWG will develop a requirements framework to validate the design space in such a way that requirements for future spacecraft, space suits, and habitats can be specified.

The following are the tentative stakeholders or designees invited to participate as members of the EAWG:

	Area of Expertise	**Name**	**Center**
1	Radiation	Barghouty, Nasser	MSFC
2	Medical	Barratt, Michael R. MD	JSC
3	Science	Buderer, Melvin C.	JSC
4	Decompression Sickness	Conkin, Johnny	JSC - NSBRI
5	Human Standards	Connolly, Janis	JSC
6	Radiation	Cucinotta, Francis A.	JSC
7	Medical	Duncan, James M.	JSC
8	Medical - EVA	Fitzpatrick, Daniel T.	JSC
9	EVA, Decompression Sickness, Crew	Gernhardt, Michael L.	JSC
10	Mission Architecture	Gruener, John E.	JSC
11	Technology Development, Integrated Testing, & Plant Growth	Henninger, Donald L.	JSC
12	EVA	Kearney, Lara E.	JSC
13	ECLSS - Advanced Life Support	Lawson, B.M. (Mike)	JSC
14	Thermal	Lin, Chin H.	JSC
15	Headquarters - Requirements Division	McCandless, Jeff	Hqs
16	Analytical Systems	Packham, Nigel	JSC
17	Structures	Pedley, Michael D. (Mike)	JSC
18	Food Systems	Perchonok, Michele H.	JSC - NSBRI
19	Materials Flammability	Ruff, Gary	GRC
20	Safety & Mission Assurance	Rust, Randolph S. (Randy)	JSC
21	EVA	Trevino, Robert	JSC
22	Materials Flammability	Urban, David L.	GRC
23	Mission Operations	Webb, Dennis J.	JSC
24	Human Factors	Woolford, Barbara J.	JSC
🟨	Confirmed as of 5-17-05		
	Chair - Don Henninger/JSC/281-483-5034		
	Deputy Chair - Paul Campbell/JSC/281-483-0079		

Table 1. Exploration Atmosphere Working Group (EAWG) roster as of 17 May 2005.

<u>Evaluate current knowledge and define viable design space</u>: July 2005

The EAWG will be comprised of experts with distinct areas of responsibility pertinent to exploration atmospheric environments. It is likely that many participants may be unaware of important requirements drivers that must be considered when undertaking such an activity. Members of the EAWG will be asked to provide a background briefing outlining their areas of responsibilities relevant to the EAWG.

Members shall describe their areas of responsibility, parametric limits under which their responsible technologies will operate, and associated risks to proper operation of their technology or responsible areas.

A compiled presentation package will be made available as a reference. Design requirements and risks will be categorized and reported as preliminary findings.

A proposed technical approach will be presented to the EAWG for general comment and consideration. This approach will be used to narrow the design space by minimizing risk factors governed by atmospheric parameters.

The EAWG will also address the following:

- Determine the “needs” vs. “wants” of each participant or stakeholder.

- Compare & contrast critical needs and risks

- Recognize overlapping areas of O_2 percent/pressure where shared requirements can be developed.

- Determine areas that have no connection but have influence on other systems, and establish connections with Interface Control Document’s (ICD’s) to outline areas of technical responsibility.

- Reference the *Bounding the Spacecraft Atmosphere Design Space for Future Exploration Missions* document.

Workshop: August 2005

The EAWG will conduct the Exploration Atmospheres Workshop. This workshop will serve as a mechanism to validate and formulate recommendations for human-occupied atmospheres and recommend additional research and technology development to enable NASA to specify exploration atmosphere requirements. Workshop activities may include the following:

- Solicit additional inputs from a NASA internal community,

- Identify additional constraints,

- Validate the proposed technical approach, and

- Concurrence of design domain.

Additional Analyses: September 2005

The EAWG shall conduct additional analyses to further refine the design space parameters. Identify and include additional information within the risk analysis.

Recommendations: September 2005

The EAWG shall make recommendations for additional research and technology development to enable NASA to specify exploration atmosphere requirements.

Final Recommendations: January 2006

The EAWG shall make final recommendations for Exploration Atmosphere Level 2 requirements. These recommendations will be reviewed with Human Systems Working Group (HSWG).

Support to Constellation Program: April –TBD 2006

The EAWG shall support the integration of these recommended requirements into the Constellation Systems requirements documentation for the *Constellation Spiral 1 System Requirements Review (SRR).*

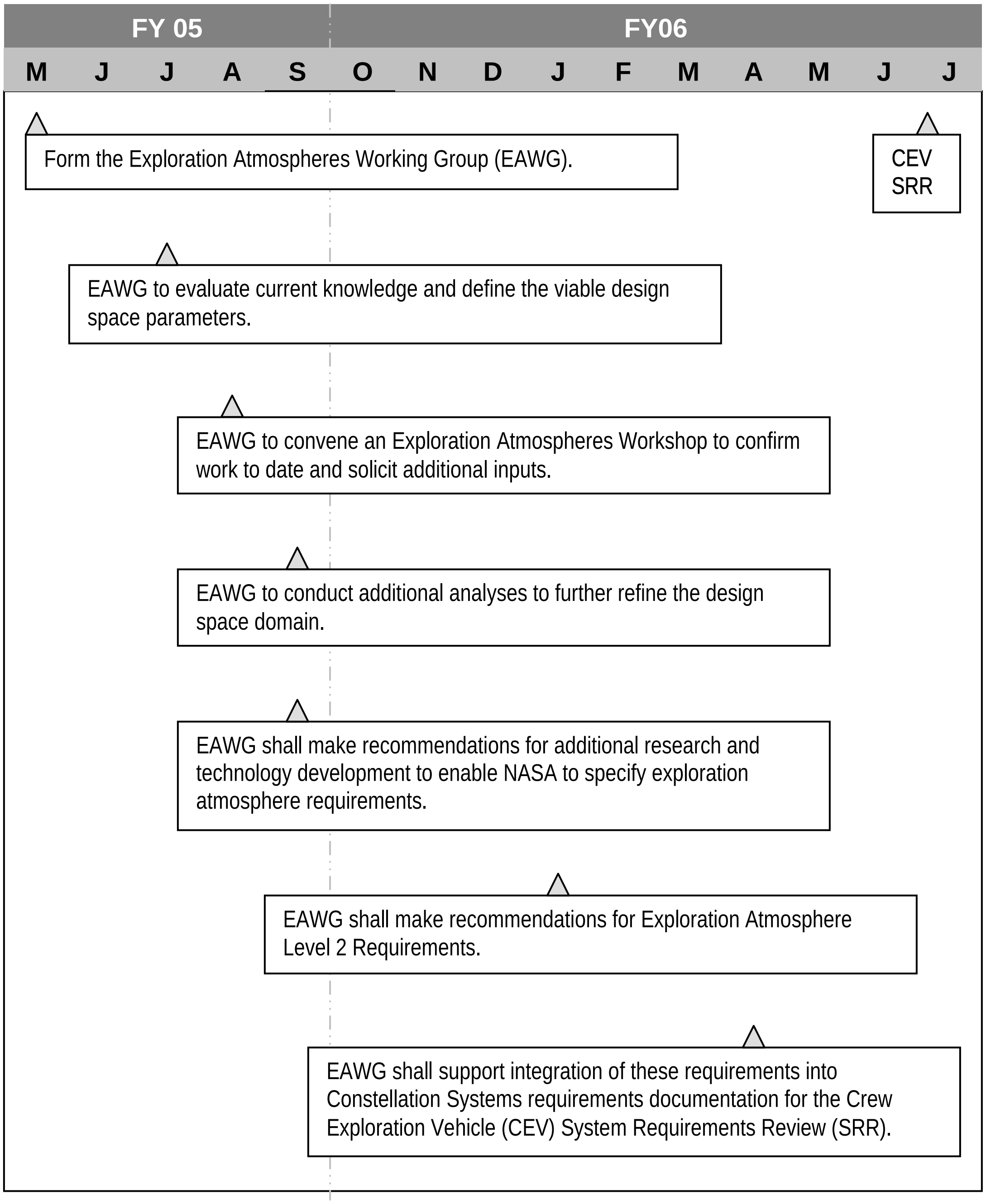
4.0 Management Plan

As a strategic investment in research and technology development The Human Systems Working Group (HSWG), in support of the Human Support Research & Technology (HSRT) Theme, has authorized the formulation of this plan.

Under sanction of HSWG, Donald Henninger (NASA/EC) is the appointed lead of this study with Paul Campbell (SA2) as the deputy.

SCHEDULE

The following timeline illustrates the approach and tentative dates that the EAWG will follow to deliver requirement recommendations.



Form the Exploration Atmospheres Working Group (EAWG).

EAWG to evaluate current knowledge and define the viable design space parameters.

EAWG to convene an Exploration Atmospheres Workshop to confirm work to date and solicit additional inputs.

EAWG to conduct additional analyses to further refine the design space domain.

EAWG shall make recommendations for additional research and technology development to enable NASA to specify exploration atmosphere requirements.

EAWG shall make recommendations for Exploration Atmosphere Level 2 Requirements.

EAWG shall support integration of these requirements into Constellation Systems requirements documentation for the Crew Exploration Vehicle (CEV) System Requirements Review (SRR).

Figure 4. Schedule of activities.

5.0 BUDGET

The following details the Exploration Atmospheres budget estimate. Existing fund sources and charge codes will be utilized.

	FY 05*		FY 06**	
	FTE	**$K**	**FTE**	**$K**
NASA FTE ($150K / FTE)	1.6	240	1.6	240
Analysis & Coordination	0.4		0.4	
Medical	0.1		0.1	
EVA	0.1		0.1	
Materials	0.1		0.1	
Structures	0.05		0.05	
Safety & Mission Assurance	0.1		0.1	
Fire Prevention, Detection & Suppression	0.1		0.1	
Advanced Life Support	0.05		0.05	
Thermal Control	0.1		0.1	
Human Factors	0.05		0.05	
Science	0.05		0.05	
Technology & Systems Development	0.05		0.05	
Mission Operations	0.05		0.05	
Programmatic & Management	0.3		0.3	
NASA Travel		15.5		15.5
Support Contractor FTE ($150K / FTE)	1.4	210	1.4	210
Support Contractor Travel & Materials		9.5		9.5
Materials - workshop		10		
Total	**3**	**485**	**3**	**475**
* 3rd & 4th Quarters of FY 05				
** 1st & 2nd Quarters of FY 06				

6.0 SUPPLEMENTAL DOCUMENTATION:

Constellation Spiral 1 Systems Requirements Review [ESMD Draft/ May 3rd, 2005]

Bounding the Spacecraft Atmosphere Design Space for Future Exploration Missions [NASA/CR-2005-DRAFT]

Appendix C:

Exploration Atmospheres Working Group
Fault Tree Analysis

Exploration Atmospheres Working Group
Fault Tree Analysis

I. Introduction

a. The Exploration Atmospheres Working Group (EAWG) is charged with refining the atmospheric design space to a relatively small domain such that atmospheric requirements for space-based systems can be specified. The EAWG will support development of requirements and integration into the Exploration Systems Mission Directorate (ESMD) Constellation Systems documentation. The working group consisted of various technical and programmatic stakeholders from across the agency including the Crew Office, S&MA, EVA, M&P, and Food Systems.

b. Fault Tree Analysis is a deductive, failure-based approach. The analysis process begins by identifying an undesirable event called a "*top event* ". Then using a system familiarization approach, determine the causes of the undesirable top event by using a systematic, backward-stepping process. This type of analysis can be either qualitative or quantitative in nature. Once the fault trees are created they can be updated and quantified as details change and mature.

c. The EAWG decided on two logic approaches: Fault Tree analysis and Analytical Hierarchical Process (AHP). It was decided to do both in parallel and compare the results prior to making any recommendations.

II. Basic Approach

a. The EAWG decided to examine nine specific atmospheric combinations that were derived in a white paper entitled "Bounding the Spacecraft Atmosphere Design Space for Future Exploration Missions" written by Kevin Lange, Alan Perka, Bruce Duffield, and Frank Jeng. The nine points are listed in Table 1 below.

Table 1

Point #1	Point #2	Point #3	Point #4	Point #5	Point #6	Point #7	Point #8	Point #9
9.4/28.5/4.3	9.3/26.8/4.3	10.6/23.2/5.0	11.6/21/6.0	12.8/21/6.0	13.2/23.1/6.0	10.2/26.5/4.3	9.5/30/4.3	8.3/36/4.3

The points are described as follows: the first number is the PSI, the second number is the PPO2 and the third number is the PSI of the EVA suit. The EAWG was divided into three teams: Mission Operations, Flammability, and Medical. Each team created fault trees within their area of expertise. The Mission Operations team initially created six fault trees, each representing a different Constellation element. The Medical team initially created two fault trees; the first dealing with Decompression Sickness (DCS) and the second dealing with Hypoxia. The Flammability team created a single fault tree. As the fault trees developed, the Mission Operations team decided that the sixth fault tree, CREW-MISSION-OPS-FTA, contained events that were being included in other fault trees and so could be deleted. The Medical team decided that the Hypoxia fault tree was not going to give any insight into the differences between the nine atmosphere points being discussed.

III. Conclusions

a. The Medical team and the Flammability team were able to rank the nine points. The Mission Operations team was unable to get the rankings completed in the time allowed during the second EAWG meeting. The Mission Operations' fault trees were not able to be completed. The results for the other two teams are shown in Table 2.

Table 2

		PSI/PPO2/EVA (Atmosphere Number)	
Risk Level	Overall Ranking Number	Flammability	DCS
Highest Risk	1	8.3/36/4.3 (9)	10.2/26.5/4.3 (7)
⋮	2	9.5/30/4.3 (8)	9.5/30/4.3 (8)
⋮	3	9.4/28.5/4.3 (1)	9.4/28.5/4.3 (1)
⋮	4	9.3/26.8/4.3 (2)	9.3/26.8/4.3 (2)
Middle Risk	5	10.2/26.5/4.3 (7)	10.6/23.2/5.0 (3)
⋮	6	10.6/23.2/5.0 (3)	13.2/23.1/6.0 (6)
⋮	7	13.2/23.1/6.0 (6)	12.8/21/6.0 (5)
⋮	8	12.8/21/6.0 (5)	11.6/21/6.0 (4)
Lowest Risk	9	11.6/21/6.0 (4)	8.3/36/4.3 (9)

These rankings were determined by simple tabulation of events ranked 1, 2, 3, etc. The point with the most events rank 1 was ranked highest risk overall and so on. This is a very basic ranking approach and can vary depending on the analyst. This method ranked the atmospheres similarly to those of the AHP and in the case of the DCS fault tree, matched rather well the calculated risk probabilities.

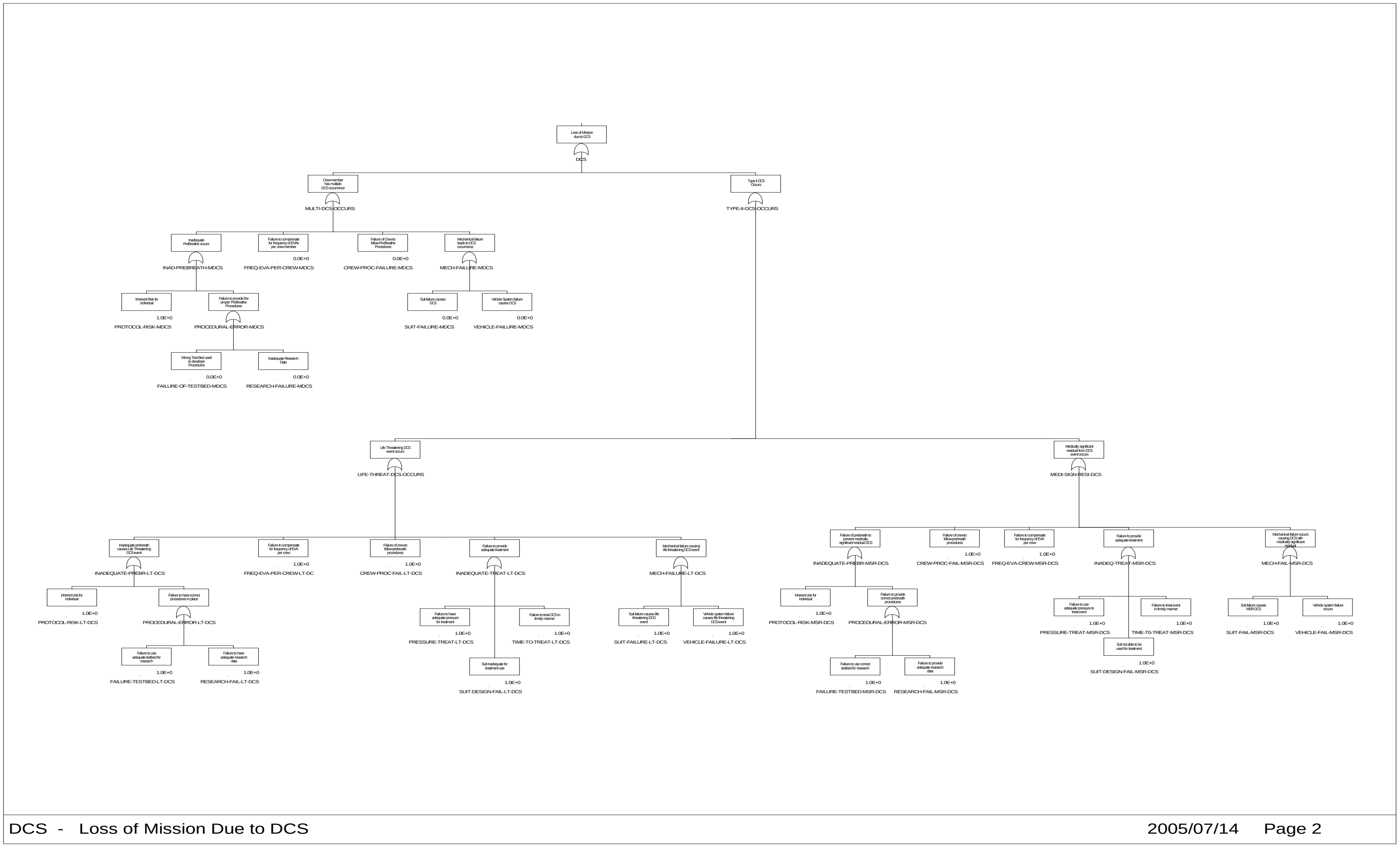
IV. Future Work

a. The current fault trees for all three teams are at an appropriate level of detail given the current program parameters. As the program matures providing more detailed parameters, the fault trees can be updated to reflect the new level of knowledge. Events can be added or subtracted as appropriate and even fault trees can be added or deleted. In the event other atmosphere points that are identified the fault trees could be used to show the relative ranking of the new points and how they relate to the original nine points. As more detail becomes available the events in the fault trees may be able to be quantified and an interval of probabilities could be determined for the risk of each point.

b. Development of the fault trees is an iterative process tool and can be used in part or in whole, by the Constellation Program PRA or by the PRAs of various projects under Constellation.

V. Appendix

a. Medical Team DCS Fault Tree



	Atmosphere Points (PSI / PPO2 % / Suit P)									
	Point #1	Point #2	Point #3	Point #4	Point #5	Point #6	Point #7	Point #8	Point #9	
Description	9.4/28.5/4.3	9.3/26.8/4.3	10.6/23.2/5.0	11.6/21/6.0	12.8/21/6.0	13.2/23.1/6.0	10.2/26.5/4.3	9.5/30/4.3	8.3/36/4.3	Comments and Rationale
Loss of Mission due to DCS										
Crew member has multiple DCS occurrence										
Failure of Crew to follow Prebreathe Procedures	5	5	5	8	5	5	1	5	9	Atmospheres with zero prebreathe have no risk of incorrectly performing prebreathe. Shuttle prebreathe is more complex than for the 60 min prebreathe atmospheres proposed
Failure to compensate for frequency of EVAs per crew member	5	5	5	8	5	5	1	5	9	Atmospheres with a smaller physiological adjustment to be made between vehicle atmosphere and suit atmosphere will have lower risk of accumulated problems.
Inadequate Prebreathe occurs										
Inherent Risk for individual	5	5	5	8	5	5	1	5	9	Assuming individual has successfully adapted to vehicle atmosphere, the scenarios that require a larger change between vehicle and suit atmosphere pose more risk for individuals.

	Atmosphere Points (PSI / PPO2 % / Suit P)									
	Point #1	Point #2	Point #3	Point #4	Point #5	Point #6	Point #7	Point #8	Point #9	
Failure to provide the proper Prebreathe Procedures										
Wrong Test Bed used to develop Procedures	4	4	4	8	7	4	1	4	9	If no prebreathe is required, procedures can't be incorrect. Higher pressure atmospheres will be easier to test and develop, and while shuttle procedures are complex, experience with them mitigates the risk somewhat
Inadequate Research Data	3	4	5	6	8	9	7	2	1	Higher pressure atmospheres will be easier to test. Shuttle atmosphere risk is mitigated by experience.
Mechanical failure leads to DCS occurrence										
(0.000E+000) Suit failure causes DCS	7	7	4	2	2	2	7	7	7	Variable pressure suits will be more complex, and thus have a higher risk. Shuttle design is not optimum design, but risk is mitigated somewhat by experience.
(0.000E+000) Vehicle System failure causes DCS	--	--	--	--	--	--	--	--	--	Depends on vehicle, not atmosphere
Type II DCS Occurs										
Life Threatening DCS event occurs										

	Atmosphere Points (PSI / PPO2 % / Suit P)									
	Point #1	Point #2	Point #3	Point #4	Point #5	Point #6	Point #7	Point #8	Point #9	
Failure of crew to follow prebreathe procedures	5	5	5	8	5	5	1	5	9	Atmospheres with zero prebreathe have no risk of incorrectly performing prebreathe. Shuttle prebreathe is more complex than for the 60 min prebreathe atmospheres proposed
Failure to compensate for frequency of EVA per crew	5	5	5	8	5	5	1	5	9	Atmospheres with a smaller physiological adjustment to be made between vehicle atmosphere and suit atmosphere will have lower risk of accumulated problems.
Inadequate prebreathe causes Life Threatening DCS event										
Inherent risk for individual	5	5	5	8	5	5	1	5	9	Assuming individual has successfully adapted to vehicle atmosphere, the scenarios that require a larger change between vehicle and suit atmosphere pose more risk for individuals.

	Atmosphere Points (PSI / PPO2 % / Suit P)									
	Point #1	Point #2	Point #3	Point #4	Point #5	Point #6	Point #7	Point #8	Point #9	
Failure to have correct procedures in place										
(1.000E+000) Failure to use adequate testbed for research	4	4	4	8	7	4	1	4	9	If no prebreathe is required, the procedures can't be incorrect. Higher pressure atmospheres will be easier to test and develop, and while shuttle procedures are complex, experience with them mitigates the risk somewhat
(1.000E+000) Failure to have adequate research data	3	4	5	6	8	9	7	2	1	Higher pressure atmospheres will be easier to test. Shuttle atmosphere risk is mitigated by experience.
Failure to provide adequate treatment										
Failure to have adequate pressure for treatment	--	--	--	--	--	--	--	--	--	Depends on architecture and treatment system selected, not atmosphere selected
Suit inadequate for treatment use	3	3	6	8	8	8	3	3	3	Variable pressure suits will be more likely to have a treatment pressure capability
Failure to treat DCS in timely manner	--	--	--	--	--	--	--	--	--	Depends on architecture and operations, not atmosphere design

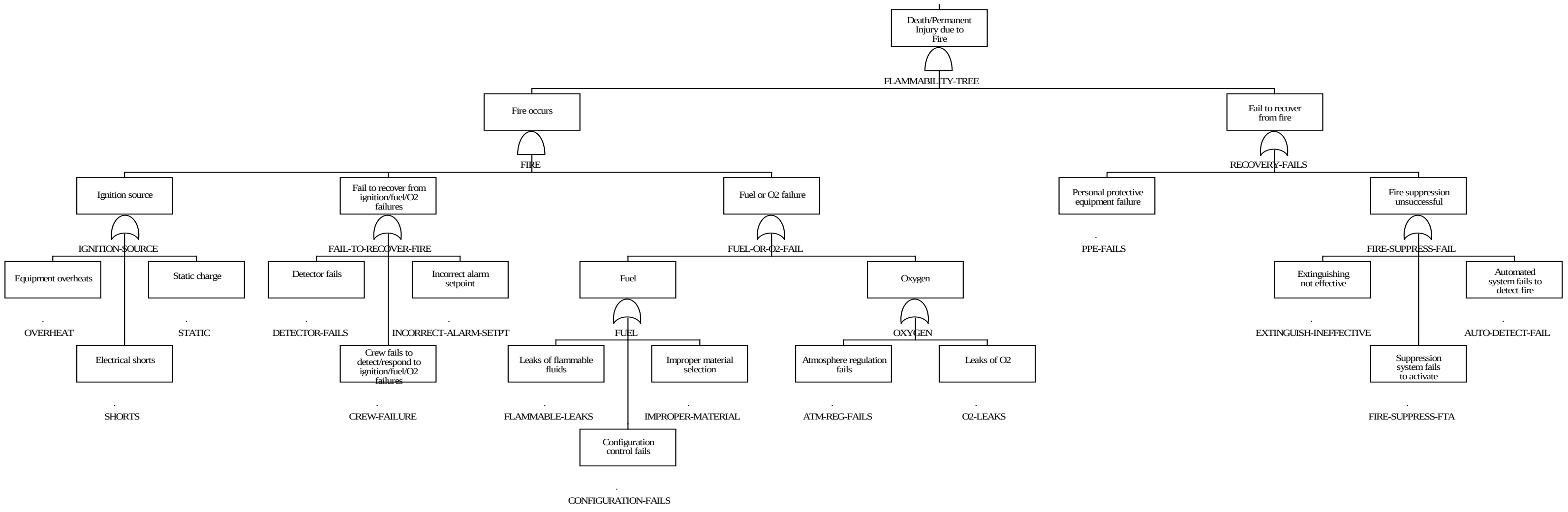
	Atmosphere Points (PSI / PPO2 % / Suit P)									
	Point #1	Point #2	Point #3	Point #4	Point #5	Point #6	Point #7	Point #8	Point #9	
Mechanical failure causing life threatening DCS event										
Suit failure causes life threatening DCS event	7	7	4	2	2	2	7	7	7	Variable pressure suits will be more complex, and thus have a higher risk. Shuttle design is not optimum design, but risk is mitigated somewhat by experience.
(1.000E+000) Vehicle system failure causes life threatening DCS event										
Medically significant residual from DCS event occurs										
Failure of crew to follow prebreathe procedures	5	5	5	8	5	5	1	5	9	Atmospheres with zero prebreathe have no risk of incorrectly performing prebreathe. Shuttle prebreathe is more complex than for the 60 min prebreathe atmospheres proposed
Failure to compensate for frequency of EVA per crew	5	5	5	8	5	5	1	5	9	Atmospheres with a smaller physiological adjustment to be made between vehicle atmosphere and suit atmosphere will have lower risk of accumulated problems.

	Atmosphere Points (PSI / PPO2 % / Suit P)									
	Point #1	Point #2	Point #3	Point #4	Point #5	Point #6	Point #7	Point #8	Point #9	
Failure to provide adequate treatment										
Failure to use adequate pressure to treat event	--	--	--	--	--	--	--	--	--	Depends on architecture and treatment system selected, not atmosphere selected
Suit not able to be used for treatment	3	3	6	8	8	8	3	3	3	Variable pressure suits will be more likely to have a treatment pressure capability
Failure to treat event in timely manner	--	--	--	--	--	--	--	--	--	Depends on architecture and operations, not atmosphere design
Failure of prebreath to prevent medically significant residual DCS										
Inherent risk for individual	5	5	5	8	5	5	1	5	9	Assuming individual has successfully adapted to vehicle atmosphere, the scenarios that require a larger change between vehicle and suit atmosphere pose more risk for individuals.
Failure to provide correct prebreath procedures										
Failure to use correct testbed for research	4	4	4	8	7	4	1	4	9	If no prebreathe is required, the procedures can't be incorrect. Higher pressure atmospheres will be easier to test and develop, and

	Atmosphere Points (PSI / PPO2 % / Suit P)									
	Point #1	Point #2	Point #3	Point #4	Point #5	Point #6	Point #7	Point #8	Point #9	
										while shuttle procedures are complex, experience with them mitigates the risk somewhat
Failure to provide adequate research data	3	4	5	6	8	9	7	2	1	Higher pressure atmospheres will be easier to test. Shuttle atmosphere risk is mitigated by experience.
Mechanical failure occurs causing DCS with medically significant residual										
Suit failure causes MSR DCS	--	--	--	--	--	--	--	--	--	New suits will be developed for exploration, so all atmospheres have risks of suit failure from new hardware
Vehicle system failure occurs	--	--	--	--	--	--	--	--	--	Depends on vehicle, not atmosphere

	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	12	0	3
2	0	0	0	2	2	2	0	3	0
3	5	2	0	0	0	0	2	2	2
4	3	6	5	0	0	3	0	3	0
5	9	9	12	0	9	9	0	9	0
6	0	0	2	3	0	0	0	0	0
7	2	2	0	0	3	0	5	2	2
8	0	0	0	14	5	2	0	0	0
9	0	0	0	0	0	3	0	0	12
	3	4	5	8	7	6	1	2	9

b. Flammability Team



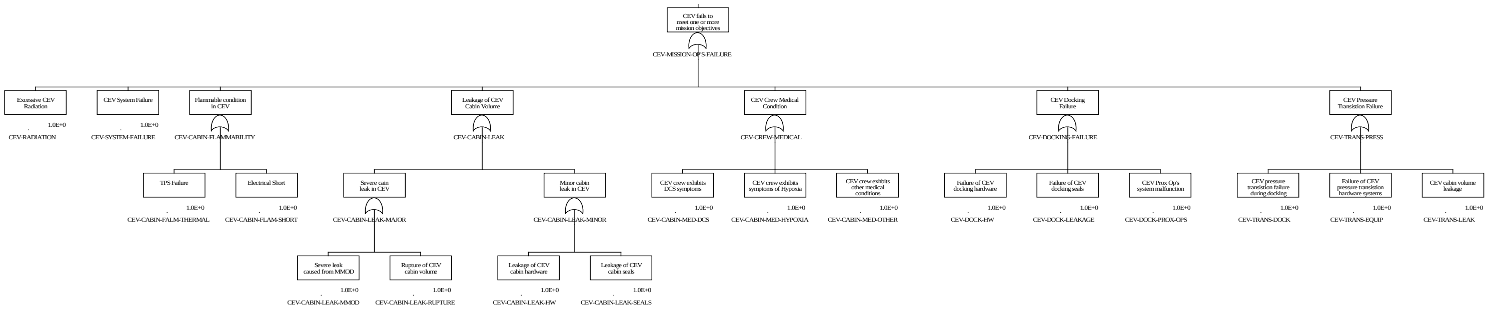
FLAMMABILITY-TREE - Death/Permanent Injury due to Fire 2005/08/09 Page 4

Fault Tree Logic for Flammability	Type	Description	Atmosphere Points (PSI / PPO2 % / Suit P)									Rationale/Comments
			9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	9.5/30/ 4.3	8.3/36/ 4.3	
Overall rankings			**3**	**4**	**6**	**9**	**8**	**7**	**5**	**2**	**1**	In general, the basic events for each atmosphere point were in agreement, so this ranking was assumed for the overall top level rankings of the atmosphere points as shown to the left. Based on the rankings, it appears that failure of the fuel or O_2 is the driver most dependent on the chosen atmosphere point, combined with overheating of equipment and ineffective extinguishing also most dependent on the atmosphere point to result in overall risk of flammability as a function of atmosphere point.
FLAMMABILITY-TREE	**Top AND Gate**	Death/Permanent Injury Due to Fire										
FIRE	**AND Gate**	Fire occurs due to combination of ignition source and fuel or O_2 failure										
FAIL-TO-RECOVER-FIRE	**OR Gate**	Failure to recover from ignition, fuel and/or O_2 failures										
DETECTOR-FAILS	Basic Event	Detector fails to detect potential fire										No effect of atmosphere selection.The only potential effect of atmosphere might be on the concentration/composition of species produced by an incipient fire.
INCORRECT-ALARM-SETPT	Basic Event	Incorrect alarm setpoint										No effect of atmosphere selection.The only potential effect of atmosphere might be on the concentration/composition

Fault Tree Logic for Flammability	Type	Description	Atmosphere Points (PSI / PPO2 % / Suit P)									Rationale/Comments
			9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	9.5/30/ 4.3	8.3/36/ 4.3	of species produced by an incipient fire.
CREW-FAILURE	Basic Event	Crew fails to detect/respond to ignition/fuel/ O_2 failures										No effect of atmosphere selection.The only potential effect of atmosphere might be on the concentration/composition of species produced by an incipient fire.
IGNITION-SOURCE	**OR Gate**	Ignition source is present										
OVERHEAT	Basic Event	Ignition source due to equipment overheats										No effect of atmosphere selection
STATIC	Basic Event	Ignition source due to static charge										Check on atmosphere dependency
SHORTS	Basic Event	Ignition source due to electrical shorts										No effect of atmosphere selection
FUEL-OR-O_2-FAIL	**OR Gate**	Fuel or O_2 failure occurs										
FUEL	**OR Gate**	Fuel failure occurs										
IMPROPER-MATERIAL	Basic Event	Improper material selection	3	4	6	9	8	7	5	2	1	Higher O_2 restricts material selection. Potential decrease in margin of safety.
FLAMMABLE-LEAKS	Basic Event	Leaks of flammable fluids										No effect of atmosphere selection
CONFIGURATION-FAILS	Basic Event	Configuration control failure	3	4	6	9	8	7	5	2	1	Higher O_2 could impose more stringent configuration control. Chance for error increases.
OXYGEN	**OR Gate**	Oxygen failure occurs										

Fault Tree Logic for Flammability	Type	Description	Atmosphere Points (PSI / PPO2 % / Suit P)									Rationale/Comments
			9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	9.5/30/ 4.3	8.3/36/ 4.3	
ATM-REG-FAILS	Basic Event	Atmosphere regulation fails	3	4	6	9	8	7	5	2	1	Lower O_2 atmospheres would allow more time for detection before O_2 concentration became high
O_2-LEAKS	Basic Event	Leaks of O_2	3	4	6	8	9	7	5	2	1	Lower O_2 atmospheres would allow more time for detection before O_2 concentration became high; points 4 and 5 reversed
RECOVERY-FAILS	**OR Gate**	Failure to recover from fire										
PPE-FAILS	Basic Event	Personal protective equipment (PPE) fails										Ask medical if 36 to 21% O_2 makes a difference
FIRE-SUPPRESS-FAIL	**OR Gate**	Fire suppression unsuccessful										
FIRE-SUPPRESS-FTA	Basic Event	Fire suppression system fails to activate										No effect of atmosphere
AUTO-DETECT-FAIL	Basic Event	Automated system fails to detect fire										No effect of atmosphere
EXTINGUISH-INEFFECTIVE	Basic Event	Extinguishing not effective	3	4	6	9	8	7	5	2	1	Higher concentrations of suppressant required to extinguish fire in high O_2

c. Mission Operations Team



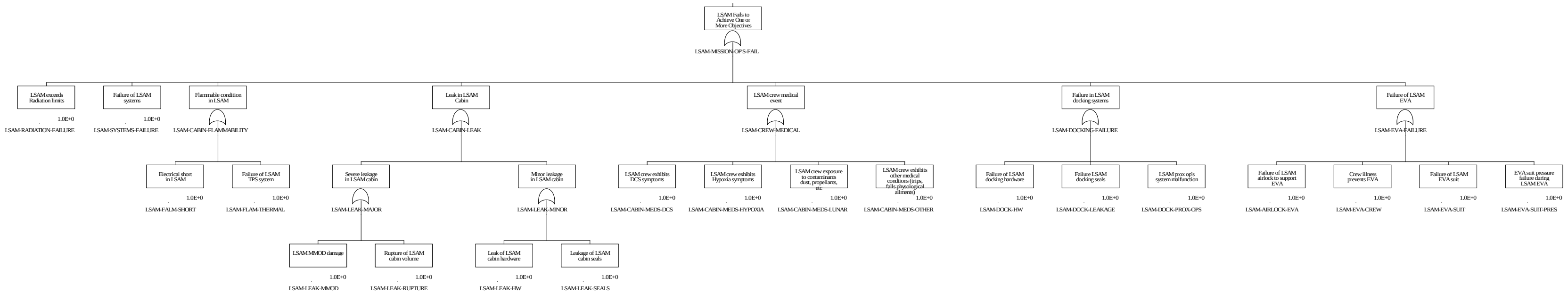
CEV-MISSION-OP'S-FAILURE - CEV fails to meet one or more mission objectives 2005/08/16 Page 2

			Atmosphere Points (PSI / PPO2 % / Suit P)									
Fault Tree Logic for CEV Op's	Type	Description	9.5/30/ 4.3	8.3/36/ 4.3	9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/ 6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	Rationale
CEV-MISSION-OPS-FAILURE	Top OR Gate	CEV fails to meet one or more mission objectives										
CEV-CABIN-FLAMMABILITY	Or Gate	Flammable condition in CEV										
CEV-CABIN-FLAM-THERMAL	Basic Event	TPS Failure										
CEV-CABIN-FLAM-SHORT	Basic Event	Electrical short										
CEV-CABIN-LEAK	Or Gate	Leakage of CEV cabin volume										
CEV-CABIN-LEAK-MAJOR	Or Gate	Severe cabin leak in CEV										
CEV-CABIN-LEAK-MMOD	Basic Event	Leak caused by MMOD										
CEV-CABIN-LEAK-RUPTURE	Basic Event	Leak caused by rupture										
CEV-CABIN-LEAK-MINOR	Or Gate	Minor cabin leak in CEV										
CEV-CABIN LEAK-HW	Basic Event	Leakage of CEV cabin hardware										
CEV-CABIN-LEAK-SEALS	Basic Event	Leakage of CEV cabin seals										
CEV-CREW-MEDICAL	Or Gate	CEV crew medical condition										
CEV-CABIN-MED-DCS	Basic Event	CEV crew exhibits DCS symptoms										
CEV-CABIN-MED-HYPOXIA	Basic Event	CEV crew exhibits Hypoxia symptoms										

			Atmosphere Points (PSI / PPO2 % / Suit P)									
Fault Tree Logic for CEV Op's	Type	Description	9.5/30/ 4.3	8.3/36/ 4.3	9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/ 6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	Rationale
CEV-CABIN-MEDS-OTHER	Basic Event	CEV crew exhibits other medical conditions										
CEV-DOCKING-FAILURE	Or Gate	CEV docking failure										
CEV-DOCK-HW	Basic Event	Failure of CEV docking hardware										
CEV-DOCK-LEAKAGE	Basic Event	Failure of CEV docking seals										
CEV-DOCK-PROX-OPS	Basic Event	CEV Prox op's malfunction										
CEV-RADIATION	Basic Event	Excessive CEV radiation										
CEV-SYSTEM-FAILURE	Basic Event	CEV system failure										
CEV-TRANS-PRESS	Or Gate	CEV pressure transition failure										
CEV-TRANS-DOCK	Basic Event	CEV pressure transition failure during docking										
CEV-TRANS-EQUIP	Basic Event	Failure of CEV pressure transition systems										
CEV-TRANS-LEAK	Basic Event	CEV cabin volume leakage										

1	Highest Risk	0	0	0	0	0	0	0	0	0
2		0	0	0	0	0	0	0	0	0
3		0	0	0	0	0	0	0	0	0
4		0	0	0	0	0	0	0	0	0
5	Medium Risk	0	0	0	0	0	0	0	0	0

			Atmosphere Points (PSI / PPO2 % / Suit P)									
Fault Tree Logic for CEV Op's	Type	Description	9.5/30/ 4.3	8.3/36/ 4.3	9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/ 6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	Rationale
	6		0	0	0	0	0	0	0	0	0	
	7		0	0	0	0	0	0	0	0	0	
	8		0	0	0	0	0	0	0	0	0	
	9	Lowest Risk	0	0	0	0	0	0	0	0	0	



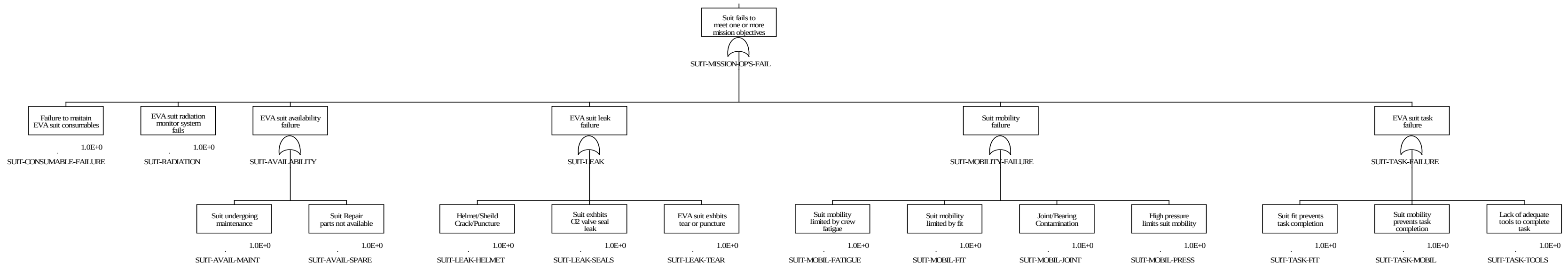
LSAM-MISSION-OP'S-FAIL - LSAM fails to meet one or more mission objectives 2005/08/16 Page 3

			Atmosphere Points (PSI / PPO2 % / Suit P)									
Fault Tree Logic for LSAM Op's	Type	Description	9.5/30/ 4.3	8.3/36/ 4.3	9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/ 6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	Rationale
LSAM-MISSION-OPS-FAILURE	Top OR Gate	LSAM fails to meet one or more mission objectives										
LSAM-CABIN-FLAMMABILITY	Or Gate	Flammable condition in LSAM										
LSAM-CABIN-FLAM-THERMAL	Basic Event	TPS Failure										
LSAM-CABIN-FLAM-SHORT	Basic Event	Electrical short										
LSAM-CABIN-LEAK	Or Gate	Leakage of LSAM cabin volume										
LSAM-CABIN-LEAK-MAJOR	Or Gate	Severe cabin leak in LSAM										
LSAM-CABIN-LEAK-MMOD	Basic Event	Leak caused by MMOD										
LSAM-CABIN-LEAK-RUPTURE	Basic Event	Leak caused by rupture										
LSAM-CABIN-LEAK-MINOR	Or Gate	Minor cabin leak in LSAM										
LSAM-CABIN LEAK-HW	Basic Event	Leakage of LSAM cabin hardware										
LSAM-CABIN-LEAK-SEALS	Basic Event	Leakage of LSAM cabin seals										
LSAM-CREW-MEDICAL	Or Gate	LSAM crew medical condition										
LSAM-CABIN-MED-DCS	Basic Event	LSAM crew exhibits DCS symptoms										

			Atmosphere Points (PSI / PPO2 % / Suit P)									
Fault Tree Logic for LSAM Op's	Type	Description	9.5/30/ 4.3	8.3/36/ 4.3	9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/ 6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	Rationale
LSAM-CABIN-MED-HYPOXIA	Basic Event	LSAM crew exhibits Hypoxia symptoms										
LSAM-CABIN-MED-LUNAR	Basic Event	LSAM crew exhibits illness due to Contaminants (Dust, Propellants, ETC.)										
LSAM-CABIN-MEDS-OTHER	Basic Event	CEV crew exhibits other medical conditions (Trips & Falls, Physiological Ailments)										
LSAM-DOCKING-FAILURE	Or Gate	LSAM docking failure										
LSAM-DOCK-HW	Basic Event	Failure of LSAM docking hardware										
LSAM-DOCK-LEAKAGE	Basic Event	Failure of LSAM docking seals										
LSAM-DOCK-PROX-OPS	Basic Event	LSAM Prox op's malfunction										
LSAM-RADIATION	Basic Event	Excessive LSAM radiation										
LSAM-SYSTEM-FAILURE	Basic Event	LSAM system failure										
LSAM-EVA-FAILURE	Or Gate	Failure of LSAM EVA										

			Atmosphere Points (PSI / PPO2 % / Suit P)									
Fault Tree Logic for LSAM Op's	Type	Description	9.5/30/ 4.3	8.3/36/ 4.3	9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/ 6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	Rationale
LSAM-AIRLOCK-EVA	Basic Event	Failure of LSAM airlock										
LSAM-EVA-CREW	Basic Event	Crew illness prevents EVA										
LSAM-EVA-SUIT	Basic Event	Failure of LSAM EVA suit										
LSAM-EVA-SUIT-PRES	Basic Event	LSAM suit pressure failure										

1	Highest Risk	0	0	0	0	0	0	0	0	0
2		0	0	0	0	0	0	0	0	0
3		0	0	0	0	0	0	0	0	0
4		0	0	0	0	0	0	0	0	0
5	Medium Risk	0	0	0	0	0	0	0	0	0
6		0	0	0	0	0	0	0	0	0
7		0	0	0	0	0	0	0	0	0
8		0	0	0	0	0	0	0	0	0
9	Lowest Risk	0	0	0	0	0	0	0	0	0

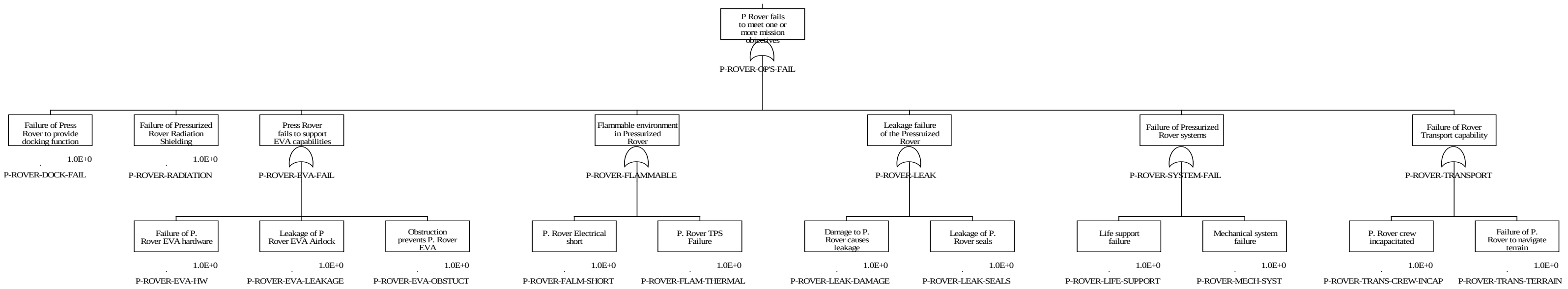


SUIT-MISSION-OP'S-FAIL - EVA suit fails to meet one or more mission objectives 2005/08/16 Page 4

			Atmosphere Points (PSI / PPO2 % / Suit P)									
Fault Tree Logic for EVA Suit Op's	Type	Description	9.5/30/ 4.3	8.3/36/ 4.3	9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/ 6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	Rationale
SUIT-MISSION-OPS-FAILURE	Top OR Gate	LSAM fails to meet one or more mission objectives	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
SUIT-AVAILABILITY	Or Gate	EVA suit Availability Failure	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
SUIT-AVAIL-MAINT	Basic Event	Suit undergoing maintenance										
SUIT-AVAIL-SPARE	Basic Event	Suit spares unavailable										
SUIT-CONSUMABLE-FAILURE	Basic Event	Failure to maintain EVA suit consumables										
SUIT-LEAK	Or Gate	EVA suit leak failure	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
SUIT-LEAK-SEALS	Basic Event	Suit exhibits leak at seal or valve										
SUIT-LEAK-HELMET	Basic Event	Suit Helmet crack or Shield puncture										
SUIT-LEAK-TEAR	Basic Event	suit exhibits tear or puncture										
SUIT-MOBILITY-FAILURE	Or Gate	Suit mobility failure	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
SUIT-MOBIL-FATIGUE	Basic Event	Suit mobility limited by crew fatigue										
SUIT-MOBIL-JOINT-CONT	Basic Event	Suit joint or bearing contamination limits mobility										
SUIT-MOBIL-FIT	Basic Event	Suit mobility limited by fit										

			Atmosphere Points (PSI / PPO2 % / Suit P)									
Fault Tree Logic for EVA Suit Op's	Type	Description	9.5/30/ 4.3	8.3/36/ 4.3	9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/ 6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	Rationale
SUIT-MOBIL-PRESS	Basic Event	High pressure limits suit mobility										
SUIT-RADIATION	Basic Event	EVA Suit radiation monitor system fails										
SUIT-TASK-FAILURE	Or Gate	EVA suit task failure										
SUIT-TASK-FIT	Basic Event	Suit fit prevents task completion										
SUIT-TASK-MOBIL	Basic Event	Suit mobility/Translation prevents task completion										
SUIT-TASK-TOOLS	Basic Event	Lack of adequate tools to complete task										

1	Highest Risk	0	0	0	0	0	0	0	0	0
2		0	0	0	0	0	0	0	0	0
3		0	0	0	0	0	0	0	0	0
4		0	0	0	0	0	0	0	0	0
5	Medium Risk	0	0	0	0	0	0	0	0	0
6		0	0	0	0	0	0	0	0	0
7		0	0	0	0	0	0	0	0	0
8		0	0	0	0	0	0	0	0	0
9	Lowest Risk	0	0	0	0	0	0	0	0	0

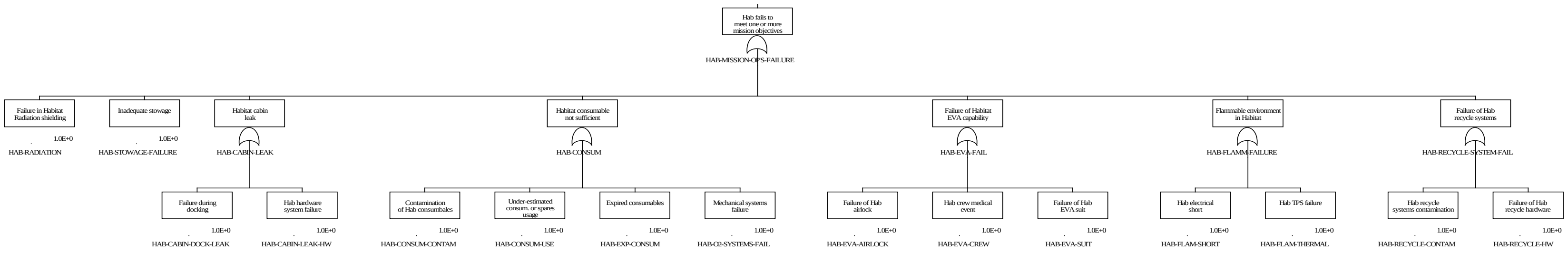


P-ROVER-OP'S-FAIL - Pressurized Rover falis to meet one or more mission objectives 2005/08/16 Page 5

			Atmosphere Points (PSI / PPO2 % / Suit P)									
Fault Tree Logic for P. Rover Op's	Type	Description	9.5/30/ 4.3	8.3/36/ 4.3	9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/ 6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	Rationale
P-ROVER-MISSION-OPS-FAILURE	Top OR Gate	P. Rover fails to meet one or more mission objectives										
P-ROVER-DOCKING-FAILURE	Basic Event	P. Rover docking failure										
P-ROVER-EVA-FAIL	Or Gate	P. Rover fails to support EVA capability										
P-ROVER-EVA-HW	Basic Event	Failure of P. Rover EVA hardware										
P-ROVER-EVA-LEAKAGE	Basic Event	Leakage at P.Rover LSAM/Hab I/F (Airlock)										
P-ROVER-EVA-OBSTRUCT	Basic Event	Obstruction prevents P.Rover EVA										
P-ROVER-CABIN-FLAMMABILITY	Or Gate	Flammable condition in P. Rover										
P-ROVER-FLAM-SHORT	Basic Event	P. Rover electrical short										
P-ROVER-FLAM-THERMAL	Basic Event	P. Rover TPS failure										
P-ROVER-CABIN-LEAK	Or Gate	Leakage of P. Rover cabin volume										
P-ROVER-LEAK-DAMAGE	Basic Event	Damage to P. Rover causes leak										

			Atmosphere Points (PSI / PPO2 % / Suit P)								
Fault Tree Logic for P. Rover Op's	Type	Description	9.5/30/ 4.3	8.3/36/ 4.3	9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/ 6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	Rationale
P-ROVER-LEAK-SEALS	Basic Event	Leakage of P. Rover seals										
P-ROVER-RADIATION	Basic Event	Excessive P. Rover radiation										
P-ROVER-SYSTEM-FAILURE	Or Gate	P. Rover system failure										
P-ROVER-ECLSS-FAIL	Basic Event	P. Rover ECLSS failure										
P-ROVER-MECH-SYS-FAILS	Basic Event	P. Rover Mechanical System failure										
P-ROVER-TRANSPORT	Or Gate	P. Rover transport failure										
P-ROVER-TRANS-CREW-INCAP	Basic Event	P. Rover crew incapacitated										
P-ROVER-TRANS-TERRAIN	Basic Event	Failure of P. Rover to translate terrain										

1	Highest Risk	0	0	0	0	0	0	0	0	0
2		0	0	0	0	0	0	0	0	0
3		0	0	0	0	0	0	0	0	0
4		0	0	0	0	0	0	0	0	0
5	Medium Risk	0	0	0	0	0	0	0	0	0
6		0	0	0	0	0	0	0	0	0
7		0	0	0	0	0	0	0	0	0
8		0	0	0	0	0	0	0	0	0
9	Lowest Risk	0	0	0	0	0	0	0	0	0



HAB-MISSION-OP'S-FAILURE - Habitat fails to meet one or more mission objectives 2005/08/16 Page 6

			Atmosphere Points (PSI / PPO2 % / Suit P)									
Fault Tree Logic for HAB Op's	Type	Description	9.5/30/ 4.3	8.3/36/ 4.3	9.4/28.5/ 4.3	9.3/26.8/ 4.3	10.6/23.2/ 5.0	11.6/21/ 6.0	12.8/21/ 6.0	13.2/23.1/ 6.0	10.2/26.5/ 4.3	Rationale
HAB-MISSION-OPS-FAILURE	Top OR Gate	HAB fails to meet one or more mission objectives	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
HAB-CABIN-LEAK	Or Gate	Habitat cabin leak	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
HAB-CABIN-DOCK-LEAK	Basic Event	Failure docking										
HAB-CABIN-LEAK-HW	Basic Event	Hab hardware failure										
HAB-CONSUM	Or Gate	Habitat consumable not sufficient	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
HAB-CONSUM-CONTAM	Basic Event	Contamination of Hab consumables										
HAB-CONSUM-USE	Basic Event	Underestimated consumable or spares usage										

			Atmosphere Points (PSI / PPO2 % / Suit P)									
HAB-CONSUM-EXP	Basic Event	Hab consumables expired										
HAB-O2-SYSTEMS-FAIL	Basic Event	Mechanical Systems failure										
HAB-EVA-FAIL	Or Gate	Failure of Habitat EVA capability										
HAB-EVA-AIRLOCK	Basic Event	Failure of Hab airlock										
HAB-EVA-CREW	Basic Event	Hab crew Medical Event occurs										
HAB-EVA-SUIT	Basic Event	Failure of Hab EVA suit										
HAB-FLAMM-FAILURE	Or Gate	Flammable environment in Habitat										
HAB-FLAM-SHORT	Basic Event	Hab electrical short										

			Atmosphere Points (PSI / PPO2 % / Suit P)									
HAB-FLAM-THERMAL	Basic Event	Hab TPS failure										
HAB-RADIATION	Basic Event	Failure in Habitat radiation shielding										
HAB-RECYCLE-SYSTEM-FAIL	Or Gate	Failure of Habitat recycle systems										
HAB-RECYCLE-CONTAM	Basic Event	Hab recycle system contamination										
HAB-RECYCLE-HW	Basic Event	Failure of Hab recycle hardware										
HAB-STOWAGE-FAIL	Basic Event	Inadequate storage										

1	Highest Risk	0	0	0	0	0	0	0	0	0
2		0	0	0	0	0	0	0	0	0
3		0	0	0	0	0	0	0	0	0
4		0	0	0	0	0	0	0	0	0
5	Medium Risk	0	0	0	0	0	0	0	0	0
6		0	0	0	0	0	0	0	0	0
7		0	0	0	0	0	0	0	0	0

			Atmosphere Points (PSI / PPO2 % / Suit P)									
	8		0	0	0	0	0	0	0	0	0	
	9	Lowest Risk	0	0	0	0	0	0	0	0	0	

Engineering and Science Contract Group
2224 Bay Area Boulevard
Houston, Texas 77058

Appendix D:

Using the Analytical Hierarchy Process to Aid in Risk Assessment for the Exploration Atmospheres Working Group

Introduction

This report explores the avenues taken by the Advanced Integration Matrix (AIM) on behalf of the Exploratory Atmospheres Working Group (EAWG) to gain EAWG consensus on possible modification of atmospheric pressure and oxygen content in order to facilitate safe and rapid Extravehicular Activity (EVA) for future long term missions. A brief questionnaire, using the Analytical Hierarchy Process (AHP) was developed to assess the qualitative preference of the group for certain proposed design points with each point having somewhat different perceived risks and rewards. A fault tree analysis was done in conjunction with this study but since there is little probabilistic data available currently comparing the key elements of the process, a qualitative ranking of design points similar to the AHP study part A was done. AHP has the capability to integrate the qualitative and quantitative data from both the simpler AHP studies and the fault tree analysis, but will rely on the opinion of experts as to the relative importance of key points such as fire risk and decompressions sickness risk to the overall risk. Previous efforts cited in the literature have shown the validity and usefulness of using AHP to combine quantitative and qualitative results in a joint effort.

Background

In order to prepare for eventual trips back to the Moon and Mars, a working group being called the EAWG was formed to study possible compromise on a vehicle/or living quarters atmosphere that might streamline and increase EVA efficiency while maintaining an atmosphere that does not significantly increase fire risk. While there are other risks which will be discussed as they are related to this subject, the efficiencies necessary to do repeated and frequent EVA is the driving force for such change. While the implications are not necessarily obvious, the ability to do the required EVA effort involves being able to rapidly and safely deploy for EVA without risk of Decompression Sickness (DCS). DCS is brought on by nitrogen or another inert gas being pulled from body tissues by a pressure gradient which occurs as a result of moving from a relatively high pressure vehicle or habitat to a relatively low pressure EVA suit. The proposed reduction in cabin/vehicle pressure would be done in order to bring the pressure closer to that of the EVA suit and thus shorten the time necessary to equilibrate the body with the space suit atmosphere. The time period required for equilibration is the prebreathe time. DCS can be prevented by a preparation via the prebreathe procedure that takes place at equal pressure to that of the vehicle/habitat, but at 100% oxygen. The oxygen gradually displaces the nitrogen in the tissues thus preventing bubbles of nitrogen from forming when pressure is reduced. If cabin pressure is high, this process can take hours and depending on the prebreathe protocol could also put the astronaut at considerable risk for DCS.

Flammability of materials increases as the volume percent of oxygen increases. As the pressure in the vehicle or habitat is decreased, the volume percentage of oxygen must be increased to keep the partial pressure of oxygen the same and allow normal lung function. According to Dalton's Law the total pressure of a gas mixture is equal to the sum of the partial pressures. If the total pressure is dropped and the partial pressure of oxygen needs to be the same for adequate lung function, then the percentage of oxygen by mass or by volume must be increased. This proposed increase in oxygen poses potential concerns. The approach taken by the fire safety community is to test all materials in well defined experimental settings and to eliminate those materials that do not pass specific tests based on flammability and off-gassing characteristics. In doing the testing up to this juncture, 30% oxygen has been considered the point where most testing stops. Therefore, few materials have been tested above the 30% oxygen limit. Though data is lacking, it is felt that many currently available materials would be lost if the proposed atmosphere is over 30% oxygen. It is believed that the electrical wire coating Nomex and the proposed radiation shielding Polyethylene could be lost if oxygen goes above 30% [1]. Possibly the flammable materials could be jacketed in metal but that could create other problems possibly related to scattering of high energy radiation particles.

These are but a few of the issues involved for the EAWG to consider. Data is both available and uncertain in some areas and in other areas totally unavailable. If risk probabilities were available for all possible events, one could use classical statistics to project the probability or likelihood of future events. However some of the activities proposed have never been done before, although data is available from similar activities for some of the proposed risk studies. There is enough difference in the areas where data was collected and analyzed as compared to the projected activity, to leave a great deal of uncertainty in the evaluation.

The Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) allows one in the absence of quantitative data or only partially available quantitative data, to combine that data with qualitative judgments to aide in evaluation of complex decisions. How much risk one proposes to take is one such complex decision. If all the necessary data was available from past experience to do a probability projection into the future, it would still tell us what designs would have failed or succeeded in the past instead of proposing ways of designing future in-system-excellence [2].

AHP has been used for risk assessment for environmental issues, national security issues, in the information technology sector and other areas and is being used to evaluate responses from the EAWG working group [3].

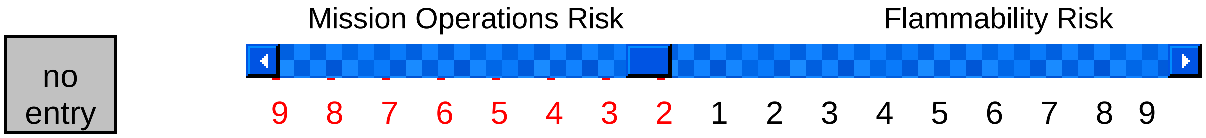
AHP uses pairwise comparisons in matrix format allowing participants to judge the importance of one item in relation to another and to make a quantitative judgment. If the participants have knowledge of the subject being considered, the AHP process captures that knowledge and assesses its consistency. An example is given in Figure 1, where each branch of a tree is evaluated against every other using a scale with magnitude 2-9 in favor of one item or 2-9 in favor of the other item. The negative signs indicate only direction toward one alternative and so for example -8 is equal to +8 in magnitude only the signs indicate preference for different alternatives. The number one means the assessment is the same for both items. The pairwise comparisons form a matrix which uses a ratio scale of paired comparisons so if a participant judges “a” more relevant than “b”, “a” is selected along with a multiplier of 1-9 and the effect of “b” on “a” is recorded as the reciprocal. A square matrix is formed with the comparisons needed to make the overall evaluation Table 1, with the comparison of each entity to itself along the diagonal and equal to 1.

Table 3-A Simple Example of an AHP Matrix for Pairwise Comparison

	a	b
a	1	8
b	1/8	1

The matrix can then be multiplied or added using standard techniques to look at how effects on a small scale affect the larger picture. The maximum eigenvalue is used to evaluate a respondent's consistency of response. An example of consistency is that if: "A" > "B"; "B" > "C" then "A" > "C".

Figure 1- Slider bar used for pairwise comparison in the AHP Assessment



A hierarchy is a representation of a complex problem in a multilevel structure whose first level is the goal followed successively by levels of factors, criteria, sub criteria, and so on down to a bottom level of alternatives [4]. The main purpose of arranging goals, attributes, issues and stakeholders in a hierarchy is that we don't have enough detail to identify a cause and effect relationship. The elements being compared should be clustered into homogenous groups so they can be meaningfully compared with respect to elements in the next highest group. Functional hierarchies decompose complex relationships into their constituent parts according to their essential relationships. A valuable observation about the hierarchical approach is that the functional representation of a system may differ from person to person but people tend to agree on the bottom level of alternative actions to be taken and the level above it.

The AHP for EAWG

The choice made for this study was to have the EAWG participants rate or rank nine design points in preferential order based on the criteria from the next tier above in the analysis, shown in Figure 8. The nine design points are outlined in Figure 2[2]. The points are bounded by a red line representing 30% oxygen which is the point to which most testing of materials for flammability has been done. The points are bounded on the bottom by the hypoxic boundary, the blue line that cuts across the page from upper left to lower right. Point nine is outside the proposed 30% boundary. The points were originally published as six design points [1], but as discussion with the EAWG progressed additional design points were added. Table 2 explains the pressure and partial pressure relationships of oxygen and the major inert gas that is present in the proposed cabin atmosphere at the proposed design points. Design points on the upper left of the design space would require prebreathe times greater than 1 hour but are assumptions based on the idea that variable pressure suits are available at 35-40 kPa and some nitrogen elimination could occur while in transit to the EVA work site.

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[2] Courtesy of Kevin Lange [1]

Figure 2-Showing the Nine Design Points Being Considered by the EAWG

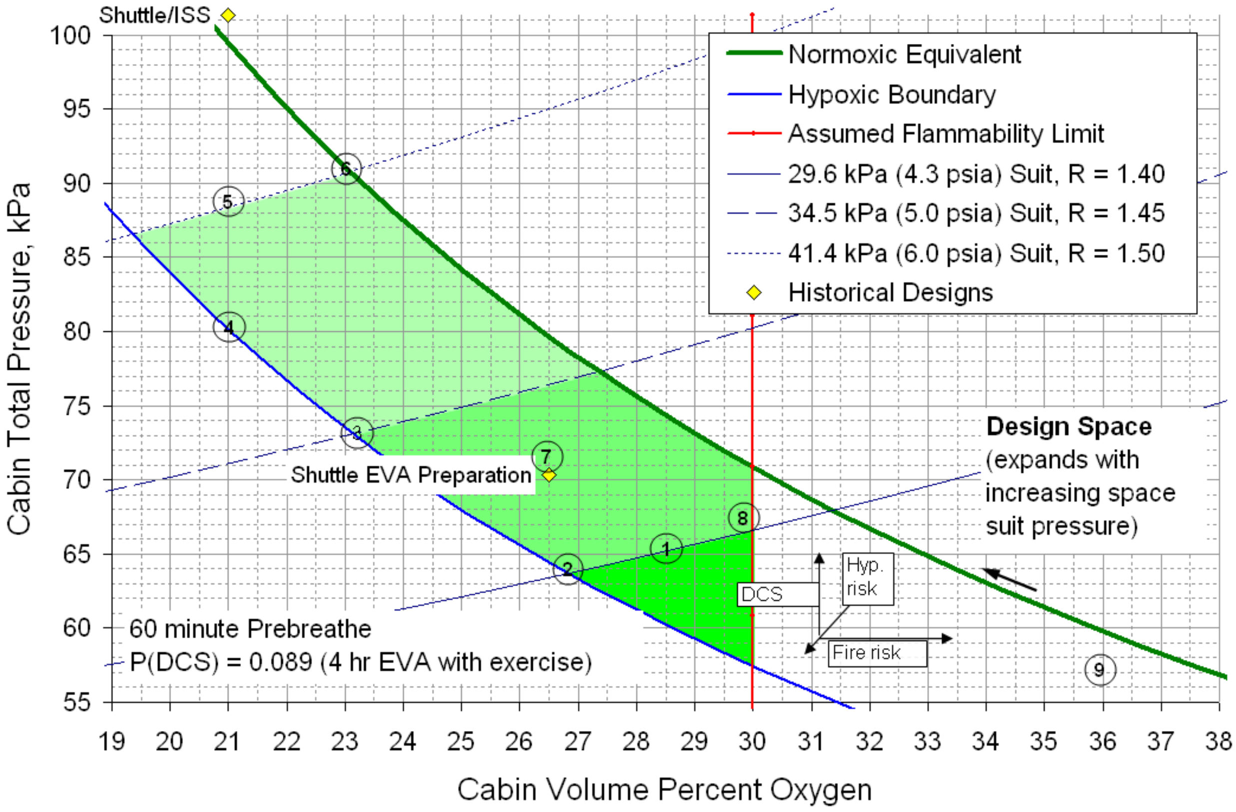


Figure 3 and Figure 4 are graphical examples of ranked design points for both Flammability and Decompression Sickness, done by EAWG members. Early in the study all participants were asked to rank the design points but after reconsideration, a decision was made to have the design points ranked by experts in four major areas: Hypoxia risk, DCS risk, Flammability risk, and Mission Operations risk. After the nine design points were ranked, all participants were asked to do pairwise comparisons on the four aforementioned areas. The comparisons serve as weighting factors on the ranking of design points and allow the design alternatives to be compared based on higher level criteria.

Table 4-Candidate Design Point Descriptions

Candidate Spacecraft and Space Suit Atmosphere Designs

Pt. No.	Cabin Pressure, kPa (psia)	Cabin ppO_2, kPa(psia)	Cabin Oxygen, volume%	EVA Suit Pressure, kPa (psia)	**General Characteristics**
1	**65 (9.4)**	**18.5(2.7)**	**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)**	**17.1(2.5)**	**26.8**	**29.6 (4.3)**	**Lowest cabin oxygen concentration with current space suit pressure; at hypoxic boundary.**
3	**73 (10.6)**	**16.9(2.5)**	**23.2**	**34.5 (5.0)**	**Moderate increase in space suit pressure with lower cabin oxygen concentration; at hypoxic boundary.**
4	**80 (11.6)**	**16.8(2.4)**	**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)**	**18.6(2.7)**	**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)**	**21.0(3.0)**	**23.1**	**41.4 (6.0)**	**Higher space suit pressure. Normoxic cabin atmosphere; slightly elevated oxygen concentration.**
7	**70.3 (10.2)**	**18.6(2.7)**	**26.5**	**29.6 (4.3)**	**Current space suit pressure. This point represents shuttle EVA preparation conditions.**
8	**65.5 (9.5)**	**19.7(2.9)**	**30**	**29.6 (4.3)**	**Current space suit pressure with assumed maximum oxygen concentration from the pressure study. O_2 concentration control limits may be outside of existing materials flammability qualification envelope.**
9	**57.2 (8.3)**	**20.6(3.0)**	**36**	**29.6 (4.3)**	**Current space suit pressure. Highest oxygen concentration point (above that assumed in the pressure study) and lowest cabin pressure minimize prebreathe time. Outside of existing materials flammability qualification envelope.**

Note: Points 1 – 6 are from Table 4.1 in Lange et. al., “Bounding the Spacecraft Atmosphere Design Space for Future Exploration Missions,” NASA/CR-2005-213689, referred to in this table as the “pressure study”. Points 7-9 were added by the EAWG after the first meeting of the group.

Figure 3-An Example of Un-weighted Ranking of Nine Design Points based on Flammability

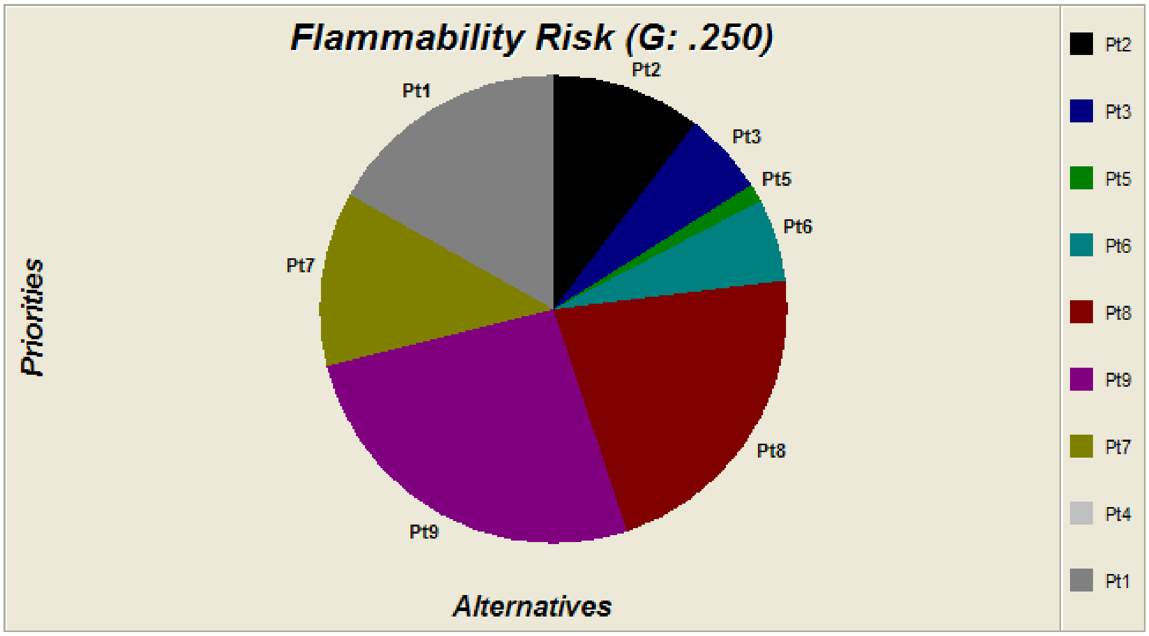
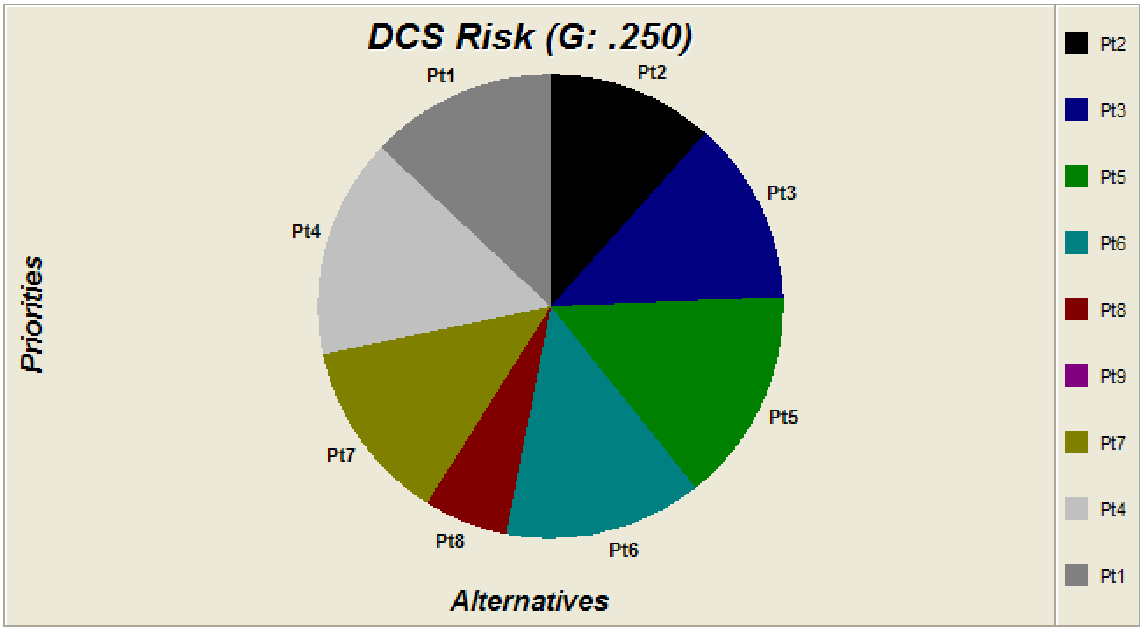


Figure 4-Figure 2-An Example of Un-weighted Ranking of Nine Design Points based on DCS



The following charts which show results of AHP analysis done by the using the software package Expert Choice. Figure 5 shows the results of the initial AHP process that made no division of the respondents based on expertise. All respondents were asked to complete all parts of the questionnaire (attached as Appendix A). A number of respondents felt uncomfortable responding to areas of the questionnaire that were out of their areas of expertise. Because of this, the survey was reanalyzed (no new questionnaire) dividing the respondents into areas of expertise and having the ranking of alternatives done by persons with expertise in the given area. Figure 7 shows the results of “experts” performing the ranking of alternatives and with the weighting factors determined by the overall group. At meeting number two, a third ranking was done with ranking of alternatives done by the experts in attendance and the weighting of objectives done by all respondents (Figure 6). Figure 6 and Figure 7 have graphical demonstrations of the contributions made in the alternative areas *i.e.* the nine ranked points. Looking at Figure 6, if there’s a substantial reduction in risk to design point 9 ranking due to low risk for DCS, it shows a shorter green section of the bar for DCS as compared to point 7 which has a high risk of DCS.

Figure 5-Chart that Demonstrates the Weighting Factors on the Left and the Results of Ranking the Nine Alternatives as influenced by the Weighting Factors; Study done prior to the second EAWG meeting with no Division based on Expertise

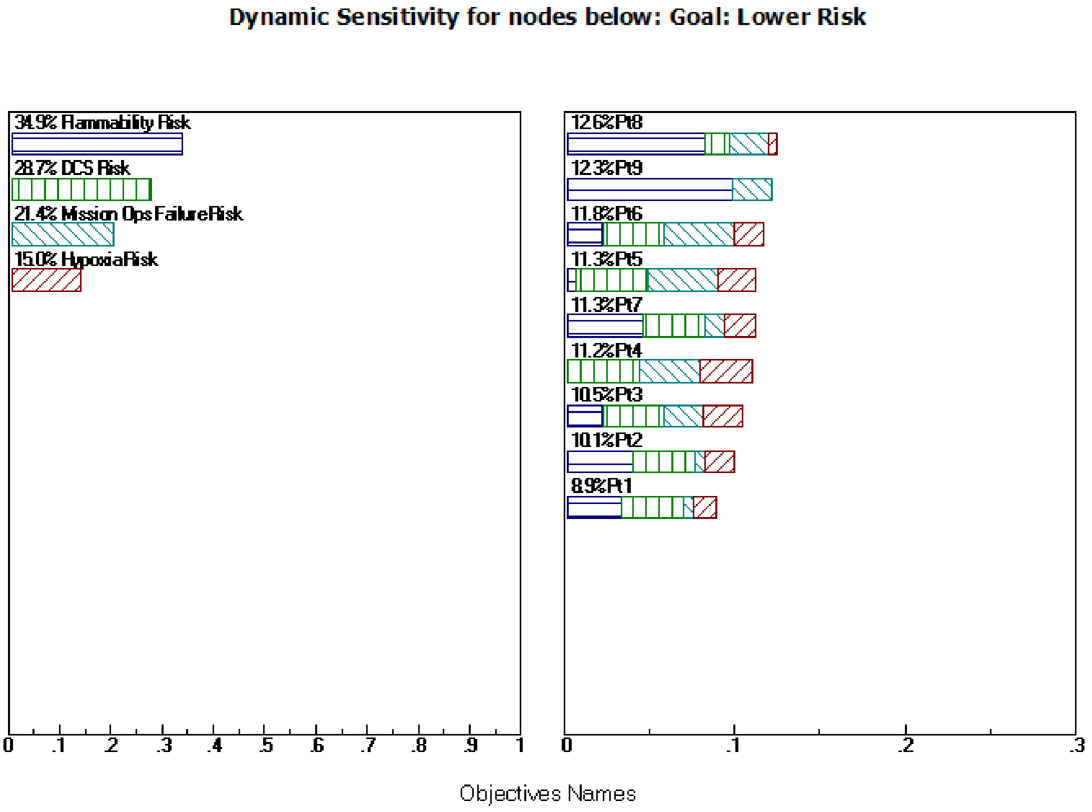


Figure 6-Chart that Demonstrates the Weighting Factors on the Left and the Results of Ranking the Nine Alternatives as influenced by the Weighting Factors; Study done during the second EAWG meeting with Division based on Expertise for Ranking the data points

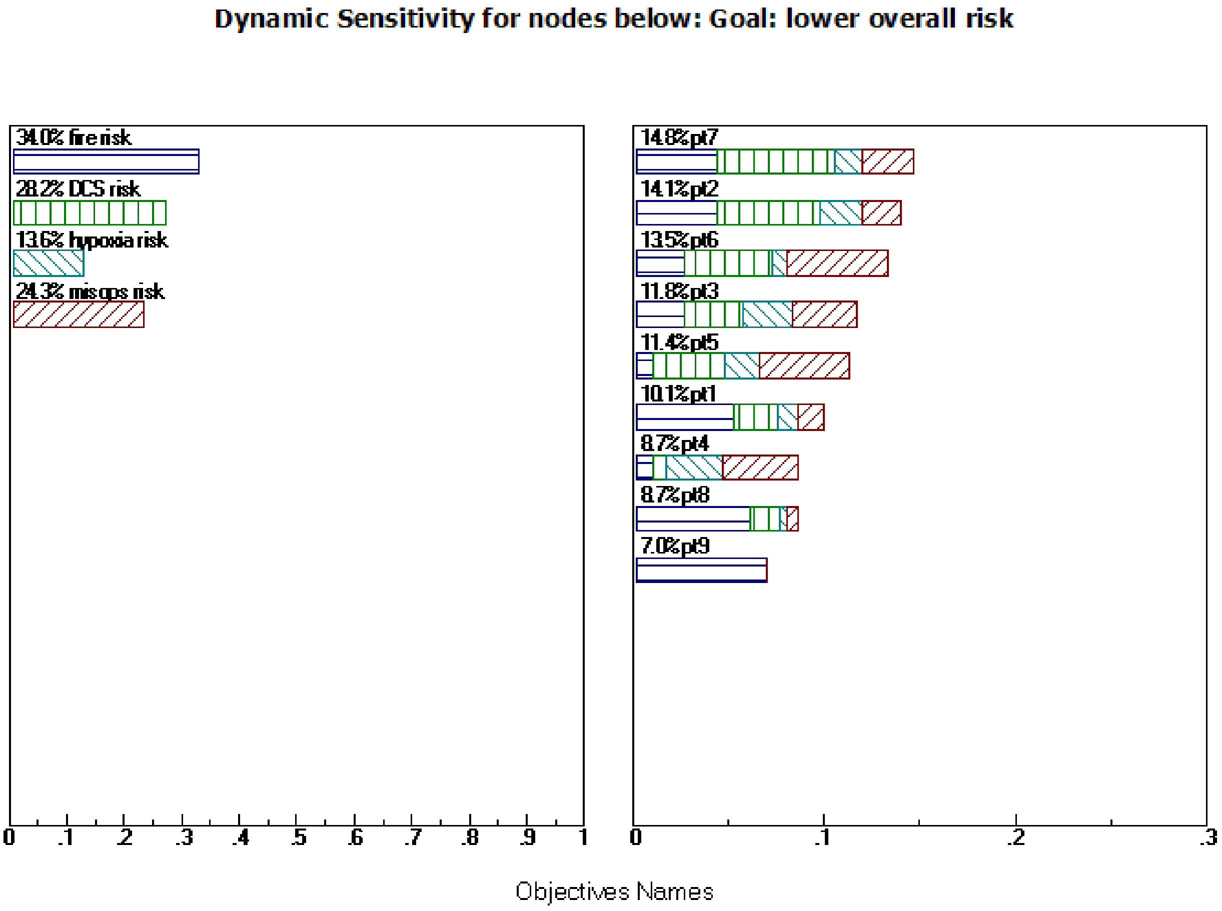


Figure 7-Chart that Demonstrates the Weighting Factors on the Left and the Results of Ranking the Nine Alternatives as influenced by the Weighting Factors; Study done prior to the second EAWG meeting with Division based on Expertise for Ranking the data points

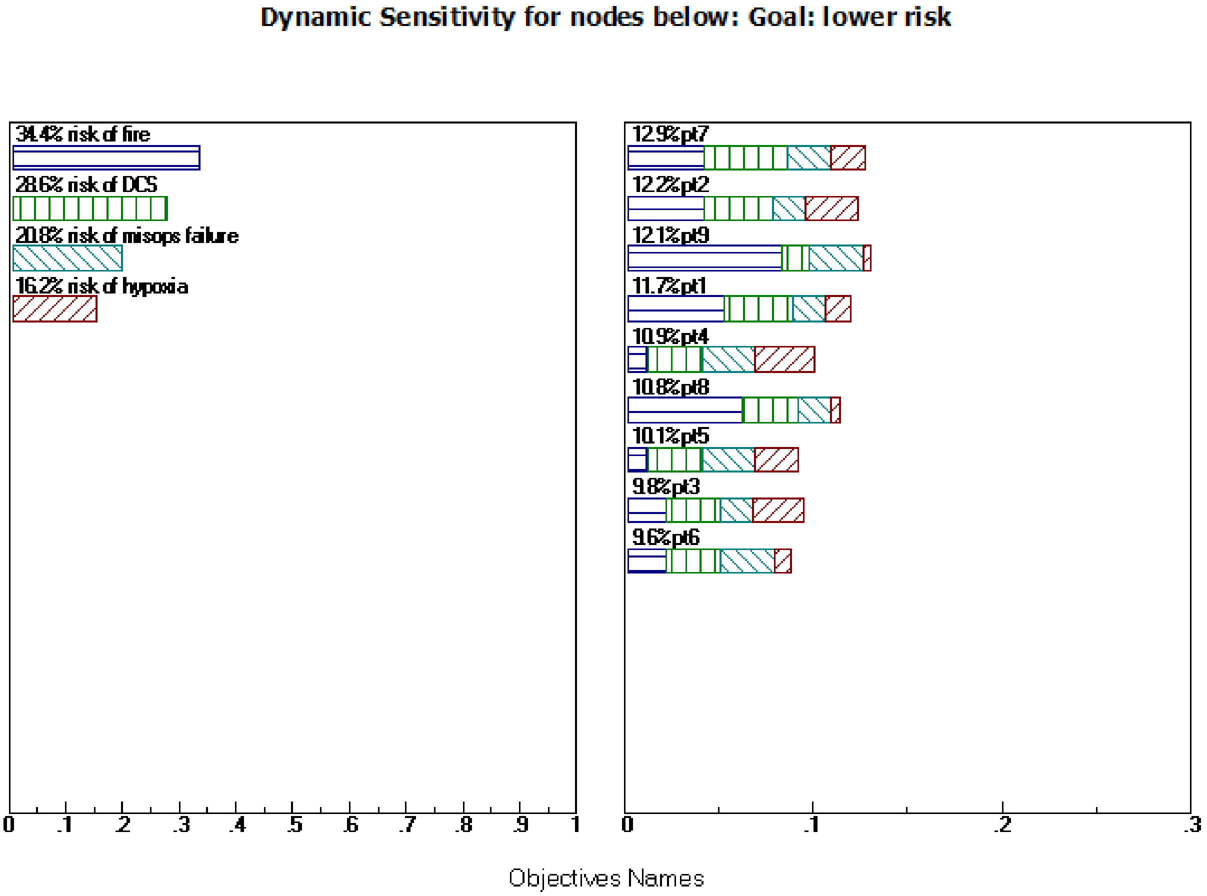
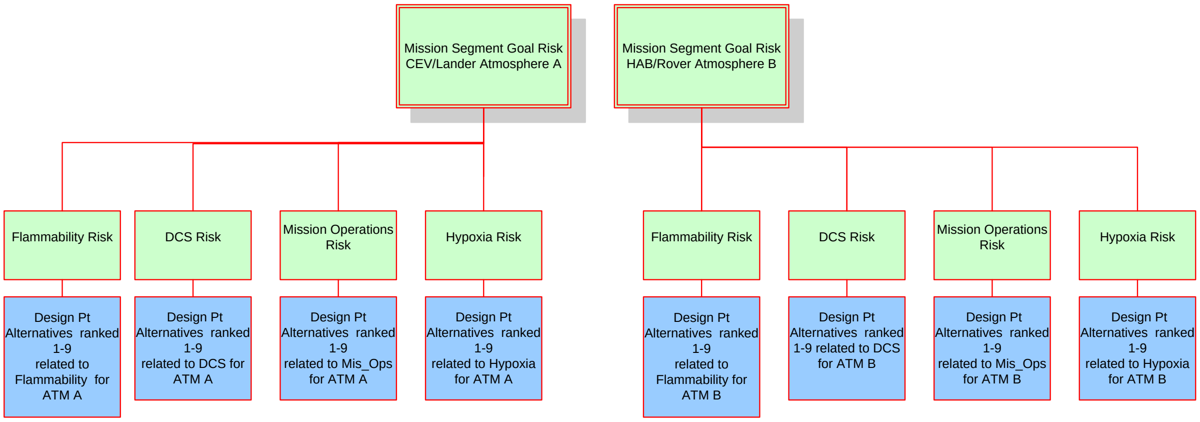


Figure 8 shows the structure of the AHP structured process used with the nine design point alternatives at the bottom of the structure and the four risk alternatives: Flammability, DCS, Mission Operations, and Hypoxia shown on the next tier above. Persons in attendance at the second meeting of the EAWG seemed most comfortable with the approach using expert opinion to perform the ranking, rather than using the entire group to rank the points.

Figure 8-Diagram of the AHP Structure as Designed for the EAWG to consider two Atmospheres: Atm. A and Atm. B.



Please Consider the Following when Rating the Design Points 1-9:

Risks Associated During Meeting 2 with Flammability:

- Level of Risk due to % O2
- Loss of Possible Materials due to Failure to Meet Fire Standards

Risks Associated During Meeting 2 with Mission Operations:

- Failure to reach EVA productivity goals
- Failure to contribute to EVA/IVA safety
- Time Required for Preparation of Safe EVA
- Glove non-flexability and Finger Injury

Risks Associated During Meeting 2 with Hypoxia

- Risk of Operation Below the Hypoxic Limit
- Risk of Failure of the O2 Support System

Risks Associated During Meeting 2 with DCS

- Lack of Timely Response to Symptoms and Treatment
- Risk Exacerbated at design point due to Strenuous EVA
- Complexity of the Pre-breath Protocol

A Parallel Fault Tree Analysis and Comparison with AHP

A fault tree analysis (FTA) is a deductive, top-down method of analyzing system design and performance. It involves specifying a top event to analyze (such as a fire), followed by identifying all of the associated elements in the system that could cause that top event to occur. Then using a system familiarization approach, it determines the causes of the undesirable top event by using a systematic, backward-stepping process. This type of analysis can be either qualitative or quantitative in nature. Once the fault trees are created they can be updated and quantified as details change and mature [5].

A parallel effort using FTA was done by the EAWG. Since there was probability data available only in the DCS category and the available data has a degree of uncertainty, having been obtained from studies which were not identical to planetary EVA, the design point alternatives were ranked in a similar 1-9 point scale, just as was done in the AHP study. Table 3 gives the rankings for the FTA process. These results are very close in the Flammability and DCS areas to AHP results.

FTA Ranking of the Nine Data Points									
Flammability (Based on Expert Judgment)	4	5	6	3	7	2	1	8	9
DCS (Based on Probability)	9	4	5	6	3	2	1	8	7
Going from left to right the most desirable point is on the left; least desirable on the right									

Table 5-Ranking of the Nine Data Points According to Fault Tree Analysis

FTA is being used to capture details of the possible cabin pressure and oxygen percentages. The rankings portion of the FTA process, and Part A of the AHP questionnaire are in general agreement, but the comparison in part B of the AHP questionnaire cross over the boundaries of many individuals expertise. In preparation for the third meeting a strategic approach was taken that assumes certain spacecraft will have equivalent atmospheres, allowing them to dock directly with each other and therefore it is assumed that:

Group A: consists of CEV, Lander, and Mars Transit Habitat/Vehicle – with the common atmosphere A.
Group B: consists of a planetary Surface Habitat, and a Pressurized Rover – and have a common atmosphere B. Atmosphere A and B may or may not be the same. Another round of AHP questionnaires were sent to the working group with exactly the same points to evaluate but for two different atmospheres. Results of that analysis will be available during the September 27-29, 2005 workshop.

The final step in the evaluation is still to make an informed assessment of the overall contribution of major risk factors. That informed assessment and recommendation, could be done with AHP, by the EAWG team after looking at all the factors involved.

Bruce E Duffield
ESCG Life Support Analyst
Thermal and Environmental Analysis Section

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Appendix E-1:

Ambulation During Extravehicular Activity on Moon and Mars as a Risk Factor for Decompression Sickness

White Paper

Authors: Johnny Conkin, Ph.D., and Michael R. Powell, Ph.D.

PURPOSE:

This White Paper documents ambulation as a risk factor for decompression sickness (DCS) during extravehicular activity (EVA) on Moon and Mars, and how to mitigate this risk through efficient prebreathe protocols.

BACKGROUND:

Standing, walking, and even stepping are such ubiquitous activities in our daily experience that healthy people do not consider these as exercise. In reality, they represent substantial lower body exercise from the standpoint of kinematics. The muscles, joints, and bones in the lower body evolved to efficiently transport a substantial mass (our body) over a long distance without difficulty. Ambulation on the Moon and Mars in a space suit will be the primary means to explore the surface. Even though the net forces transferred to the lower body will be lower in a reduced gravity field and the range and rate of joint motion will be reduced due to the suit exoskeleton, ambulation still represents the greatest expenditure of energy during the EVA(12).

It is well documented (1,3,5,6,10) that exercise of the lower body increases the risk and severity of Type I "pain-only" decompression sickness (DCS) in the feet, ankles, knees, and hips. It is beyond the scope of this White Paper to review the mechanisms to account for increased risk due to ambulation (see Appendix for some details). Suffice it to say that there is no disagreement that lower body exercise increases the risk of DCS and the number of venous gas emboli (VGE). But there is disagreement on the magnitude of the effect (3,7,8,9,11). Much of the disagreement is because several factors determine the magnitude of the effect, such as the magnitude of decompression stress at the start of the exercise, the type and intensity of lower body exercise, and even the time spent walking at reduced pressure. An understanding of the risk with each of these factors in isolation has not been achieved, so opinions vary.

Ambulation as a factor to increase the risk of DCS is not a concern if nitrogen (N_2) pressure in the tissues is less than total suit pressure. Under this condition, there is no N_2 supersaturation in the tissues during EVA, and bubble formation and growth is not possible. This was the case during the Apollo program where astronauts lived at 5.0 psia in 100% oxygen (O_2) for several days prior to EVA on the Moon in 3.7 psia suits. However, future exploration missions to Moon and Mars will be conducted from habitats that have an inert diluent gas. The presence of this gas, most likely N_2, and the possibility of operating at a suit pressure lower than the habitat diluent pressure makes ambulation a risk factor for DCS and VGE. The risk can be mitigated through a combination of habitat atmosphere selection, additional in-suit prebreathe, or a higher suit pressure.

FUNDAMENTAL ASSUMPTION:

The assumption here is that any prebreathe compensation to reduce the risk of DCS and VGE due to ambulation on Earth would be as effective applied to ambulation on Moon and Mars. Note that the acceptable level of DCS risk for Moon and Mars missions has not been determined.

Example of ambulation as a risk factor for DCS and VGE, and how to mitigate this risk with additional in-suit prebreathe:

A detailed example, based on analysis, is now provided to demonstrate the magnitude of the ambulation effect on DCS and VGE risk and the magnitude of the prebreathe compensation needed to mitigate the ambulation effect.

The successful 10.2 psia staged decompression protocol currently used on the Shuttle is one option for the Crew Exploration Vehicle (CEV) and Moon habitat. But EVA on the Moon or Mars will involve significant ambulation, possibly quite different than on Earth (Moon Loping (12)), and it is possible that the current Shuttle staged decompression protocol would need to be more conservative for use on the Moon (see Figure 1).

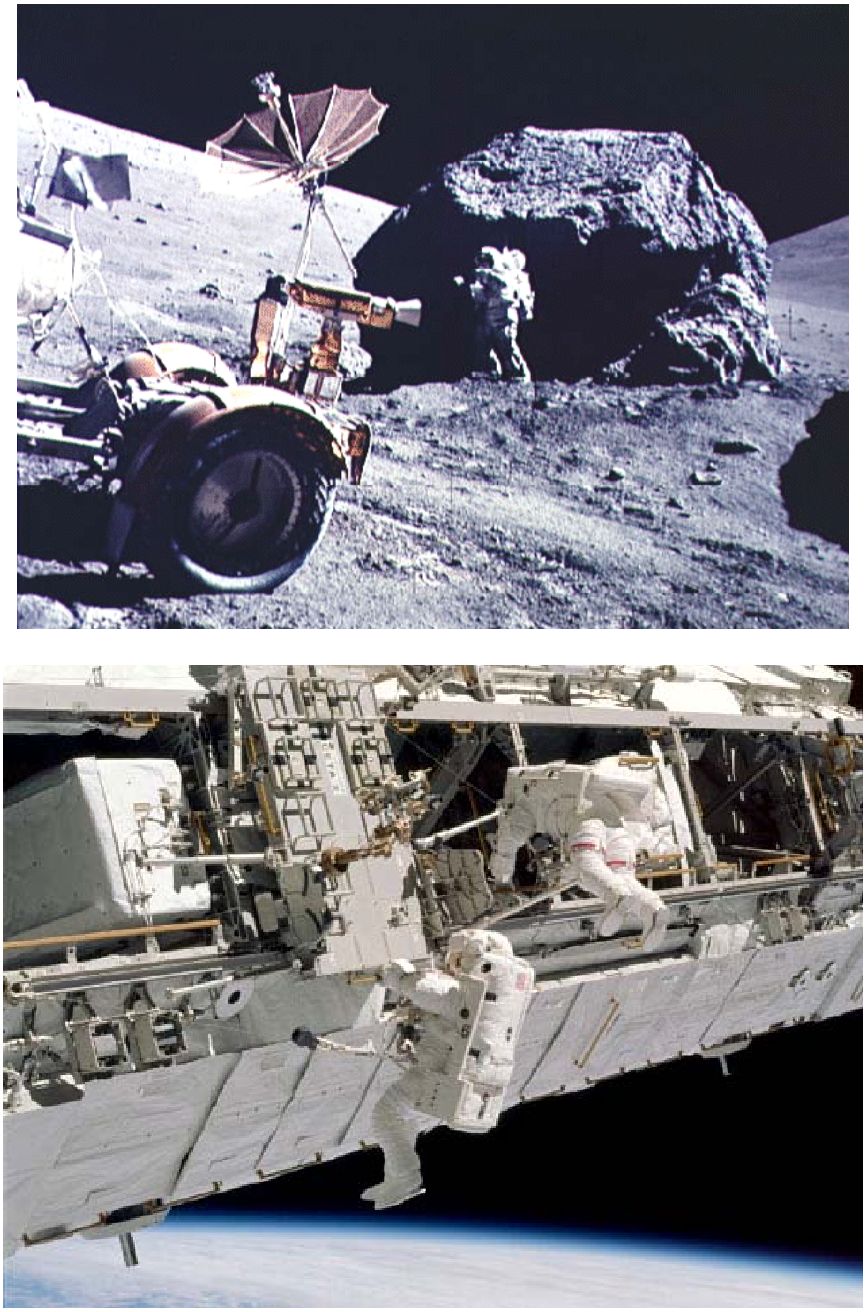

Figure 1. Because of musculoskeletal stress, these are not equivalent activities when assessing the risk of DCS.

Details about the Space Shuttle Staged Protocol:

The Shuttle cabin initially operates at 14.7 psia, at about 21% oxygen. There is an initial 60 min 100% O_2 mask prebreathe at 14.7 psia if subsequent time at 10.2 psia is less than 36 hrs, or else the initial prebreathe is omitted. Before EVA, the EVA crewmembers don space suits. The final in-suit prebreathe depends on the time spent at 10.2 psia breathing 26.5% O_2; it is 75 min if equilibrated for 12 hrs and 40 min if equilibrated more than 24 hrs. Finally, the EVA crewmembers decompress to 4.3 psia in their suits.

Details about computed Tissue Ratio (TR) as an Index of Decompression Stress:

TR is $P1N_2$ / P2 where $P1N_2$ is calculated N_2 pressure in a compartment with a 360 min half-time just prior to EVA, and P2 is 4.3 psia for the current EVA suit. The staged protocol provides denitrogenation through a combination of 100% O_2 prebreathe with a mask and in the suit, and several hrs of breathing a reduced ambient ppN_2 of 7.5 psia. Equilibration at a ppN_2 of 7.5 psia plus 70 min of additional in-suit prebreathe results in a computed TR of 1.524.

We computed TR from 143 staged Shuttle prebreathe protocols performed in flight. The results from 80 of the 143 total EVAs done first from the Shuttle are compared to 245 prebreathe tests performed in altitude chambers at the Johnson Space Center (JSC).

The presence of Doppler-detected gas bubbles (VGE) in the pulmonary artery (venous blood) was determined with an ultrasound Doppler bubble detector in the tests performed in altitude chambers.

Refer to Figs. 2 through 4 for a summary of our analysis.

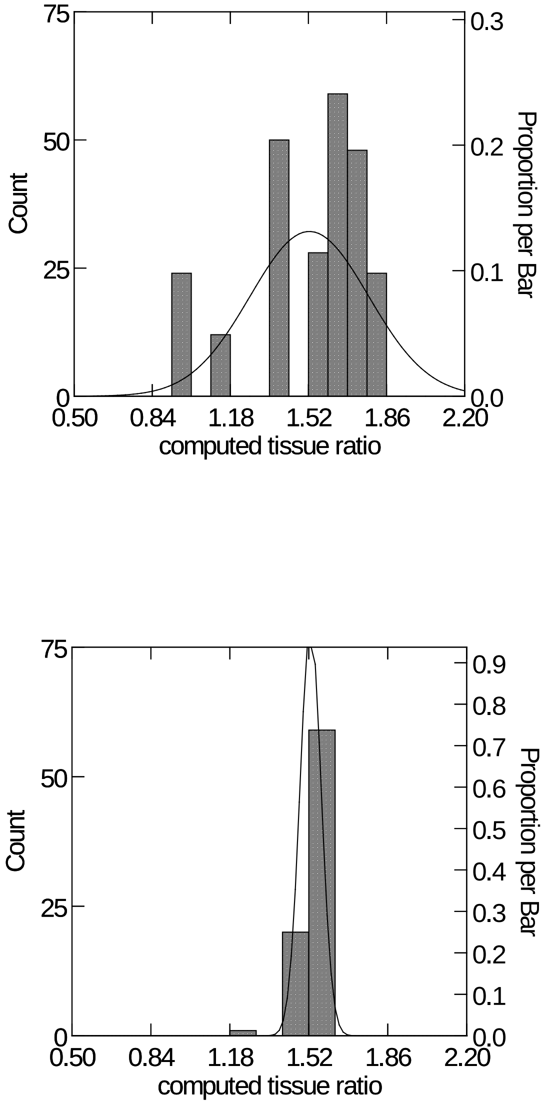

Figure 2. Histograms showing the distribution of computed tissue ratio in the 245 records from subjects in altitude chambers at JSC (upper) and 80 records of astronauts that performed their first 10.2 psia staged EVA from the Shuttle (lower). A normal density function is imposed on each histogram to provide a visual reference to each mean computed tissue ratio (peak of curves) and the variability about each mean (spread of curves). The means are very similar, about 1.52, but the standard deviation is five times smaller in the EVA data (0.046) compared to the chamber data (0.26).

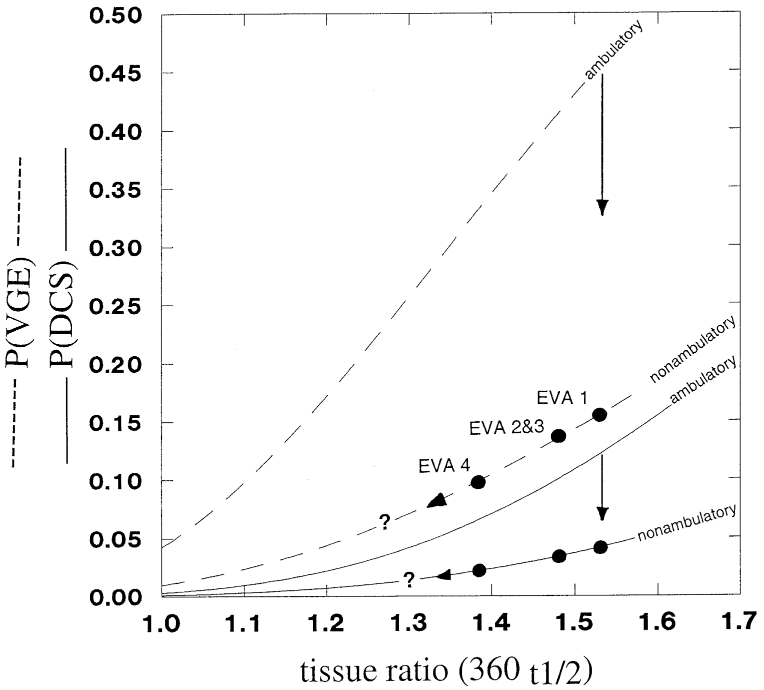

Figure 3. The probability of DCS [P(DCS)] and probability of VGE [P(VGE)] decreases on subsequent EVAs after the first EVAs from the Shuttle (from Conkin, 2001). All 143 EVAs were performed after > 12 hrs of denitrogenation at 10.2 psia while breathing 26.5% O_2. Eighty of the 143 EVAs were the first EVAs of the mission. The predicted risk of DCS and VGE are greater than zero in both cases, but no DCS has been reported during EVA, and VGE have never been monitored during EVA to confirm the predicted risk. Note the impressive decrease in DCS and VGE risk when the nonambulatory condition (no use of weight bearing leg muscles) is present, which we consider is present during EVAs from the Shuttle.

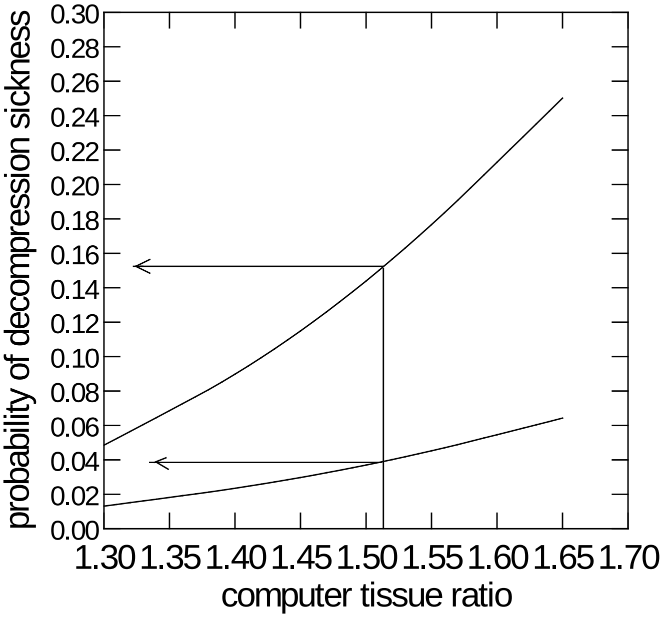

Figure 4. At a computed tissue ratio of 1.52, the best estimate of DCS risk after 80 Shuttle staged denitrogenations given nonambulatory EVA is about 4% compared to 15% if the same EVA is done under ambulatory conditions (from Conkin, 1996). The contribution of ambulation toward the risk of DCS is a significant unknown if EVAs are done on the Moon and if the Shuttle staged denitrogenation protocol were adopted for the Moon habitat.

Table I is a summary of the observed and predicted risk of DCS from EVA and research experience. Notice that the mean TR of 1.52 from 80 of 143 total EVAs done first from the Shuttle is comparable to 245 research tests in altitude chambers. But there was 18.3% (13.7 – 23.8%, 95% confidence interval (CI)) DCS observed in ambulatory subjects in altitude chambers compared to no DCS (0 – 4.5% CI) reported from astronauts during EVA. The risk of DCS for a 1.52 TR is predicted higher for ambulatory EVAs on the Moon [15.5% (0 – 32% CI)] compared to nonambulatory EVAs from the CEV [4.0% (2 – 8% CI)]. Also notice that the predicted risk of 15.5% for ambulatory EVAs on the Moon is comparable to the 18.3% risk for ambulatory subjects in altitude chambers.

TABLE I: Observed and Predicted Risk of DCS

Test Condition	TR ± SD, n	Observed %DCS (CI)	Predicted %DCS (CI) μg EVA (3)	Predicted %DCS (CI) Moon EVA (2)
Flight μg	1.527 ± 0.046, 80	0% (0 – 4.5)	4.1% (2 – 8)	15.9% (0 – 34)
Research 1g	1.520 ± 0.26, 245	18.3% (13.7 – 23.8)	4.0% (2 – 8)	15.5% (0 – 32)

CI = 95% confidence interval

CONCLUSIONS

- DCS has not been reported during EVAs at 4.3 psia from the Shuttle, so a similar staged protocol for the CEV will likely result in similar success.
- Inactivity of the lower body in μg before and during EVA likely reduces the risk of Type I DCS in the lower body, but ambulation on the Moon and Mars given the same TR is predicted to quadruple the risk of DCS and triple the risk of VGE to a level observed during ambulatory tests in JSC ground-based altitude chambers.
- A long final in-suit prebreathe time of 2.5 hrs may be required if the current Shuttle staged protocol were adopted for a Moon habitat to compensate for ambulation on the Moon (see Fig. 5), and even longer if suit pressure were less than 4.3 psia.
- At present, there is no good estimate of what the type of walking referred to as “Moon Loping” will have on bubble formation in tissues.

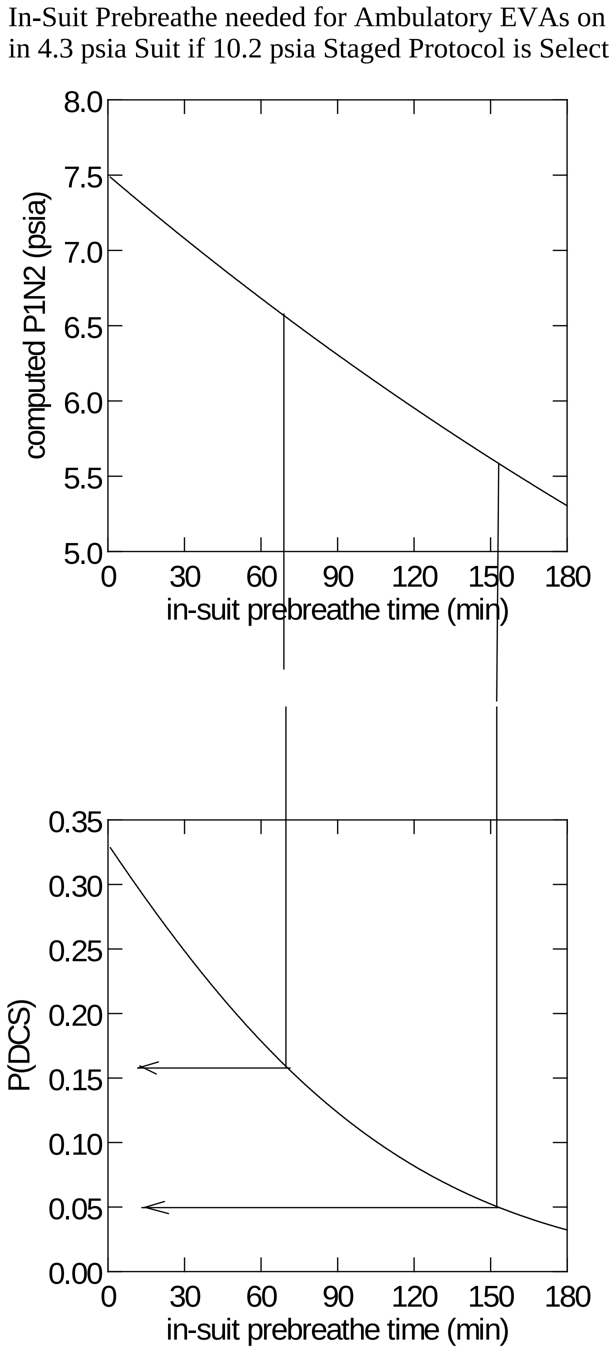

Figure 5. To compensate for the increased risk of DCS and VGE at 4.3 psia due to ambulation on the Moon, additional in-suit prebreathe time is required to reduce the risk if the current 10.2 psia staged conditions are selected for a Moon habitat. The acceptable level of DCS risk for Moon EVAs has not yet been defined.

- Therefore a different staged protocol is also a consideration to reduce the total prebreathe time to 60 min. For example a 9 psia habitat with 30% O_2 would result in about 5% risk of DCS at 4.3 psia, or a 8.3 psia habitat with 36% O_2 would result in about 1% risk of DCS at 4.3 psia (see Fig. 6).

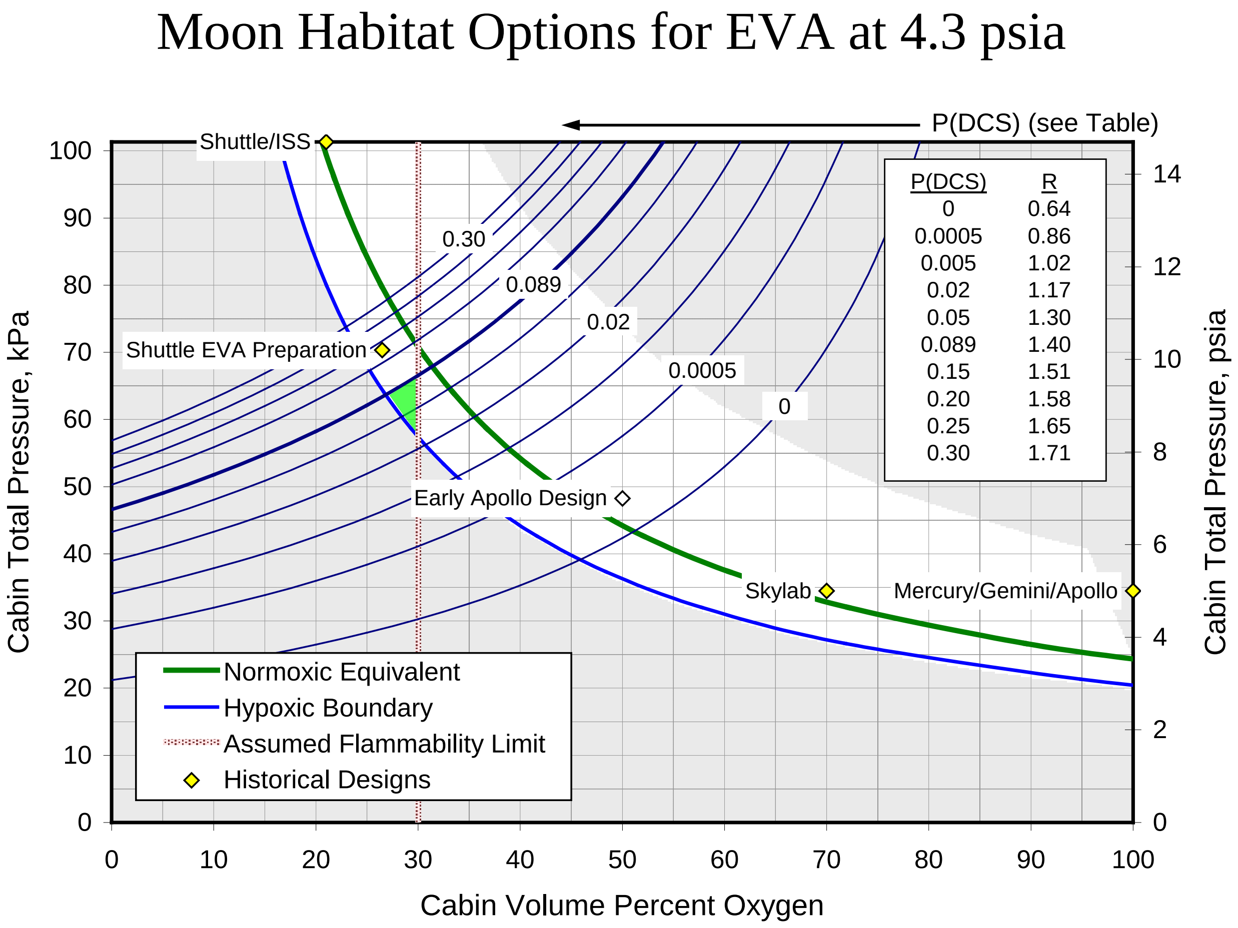

Figure 6. Curves for constant DCS probability (isorisk) from Conkin, 1996 for a 29.6 kPa (4.3 psia) space suit with a 60 min prebreathe (6.89 kPa = 1.0 psi). Calculations based on a four hr EVA on the Moon that includes exercise plus ambulation equivalent to walking in 1-g. If prebreathe time is limited to 60 min, and acceptable DCS risk is < 10%, then the resulting narrow design space for the Moon habitat is restricted to the shaded region. Figure from Lange, 2005.

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APPENDIX

Discussion about Lower Body Adynamia

"Space walk" during an EVA in low Earth orbit is a misnomer. Astronauts do not walk in the conventional sense but only anchor their legs to a stable structure so that the upper body can affect some task. We characterize the lack of musculoskeletal activity and therefore the lack of dynamic forces in the lower body over several days of adaptation to μg and during EVAs as Lower Body Adymania (LBA). We define LBA as restricted lower body movement, particularly walking or even a standing posture through contraction of antigravity musceles, during both the denitrogenation phase (prebreathing) at site pressure and during the exercise phase while at altitude. In simpler terms, if you do not ambulate (walk) in a gravity field, then you are considered adynamic.

LBA is a condition of sufficient magnitude to reduce the risk of DCS and VGE. A person who is inactive, more specifically neither standing erect nor walking, before and during a prebreathe and while at altitude is less likely to have DCS or VGE than the same person who is inactive at altitude but walks both before and during the exposure. The mean latency times of the first symptom and VGE are extended in adynamic subjects compared to ambulatory subjects. We feel there is enough data to recommend LBA as a technique to use before and during an altitude exposure if the goal is to reduce the risk of DCS and VGE, or reduce the variability in the DCS and VGE outcome for some people. We cannot say that adynamia before or during the exposure is more important since these data are not yet available. Our working hypothesis is that any benefit derived from adynamia before an exposure is lost if the adynamia is not maintained during the exposure because of the rapid regeneration of tissue micronuclei.

The fundamental question about mechanisms to account for the observations about LBA cannot be answered here. We observe macroscopic outcomes and then infer mechanisms on a microscopic scale. A comprehensive review and discussion of micronuclei is beyond the scope of this report, but information is available (1,2,3). The fundamental untested premise of adynamia is about the control of nucleation processes within tissues and fluids. In the absence of supersaturation (the difference between dissolved gas partial pressure and the absolute pressure), the spontaneous rate of nucleation is inconsequential when micronuclei on the order of microns in radius are considered. This is not to say, however, that the number or distribution of micronuclei sizes cannot be influenced before a supersaturation exists when mechanical energy is added to the system. A case in point is the observation that vigorous exercise during a 90 min prebreathe reduces, not increases, the incidence of DCS and VGE (4,5). The enhanced removal of N_2 during the dual-cycle exercise appears to dominate the DCS and VGE outcomes, regardless of how the number or distribution of micronuclei was changed.

There are at least four areas that we contemplate when considering micronuclei: the rate of micronuclei formation, the number of micronuclei formed, the distribution of micronuclei size, and the rate of micronuclei dissolution, which includes mechanisms to stabilize micronuclei. Each of these processes is complex to characterize in a physical system and more so when energy is added too or subtracted from a biological system. For example, the mechanical energy transferred through tendons and ligaments from muscle contractions. Supersaturation could be tolerated indefinitely if the rate of nucleation or rate of bubble growth were very slow. Therefore, the full potential for evolved gas as bubbles would not be realized if the supersaturation is reduced by the blood's removal of dissolved gas faster than either the rate of nucleation or the rate of bubble growth. The rate of nucleation for a given supersaturation may not be a rate-limiting step in bubble formation because there may be stabilized or easily formed micronuclei that exist in the body. Thus, the appearance of bubbles after decompression may depend simply on the growth of readily available micronuclei, and well-controlled experiments can help to resolve the mechanism(s) of adynamia. Stephan (viscous) adhesion or tribonucleation (6,7,8,9), either before or after a decompression, is a process that could increase the rate of nucleation in living tissue and fluids, so experiments about micronuclei before a decompression should eliminate tribonucleation as a variable after the decompression. To complete the discussion, there is evidence that preformed and stabilized micronuclei do not exist before decompression, at least in a species of translucent crab (2,10).

We postulate that with an adynamic period of several hrs, a new distribution of micronuclei is established. The larger micronuclei are unstable and therefore short-lived and, in part due to surface tension (16), fewer stabilized smaller micronuclei transform into growing bubbles for a given supersaturation (15). The application of a high pressure spike, either hydraulic or pneumatic, filtration, or ultracentrifugation of a sample, are all accepted means to reduce the number and size of micronuclei (change the distribution) as evident by fewer bubbles or cases of DCS after a subsequent decompression (6,8,11). The idea of "using up" micronuclei faster than they are generated as a means to understand increased resistance to DCS on repeated exposures has also been discussed (1).

Our approach to use LBA to reduce or otherwise control hypothetical micronuclei populations appears to be the first use of this concept, especially as it applies to decompressions in μg. Violent muscular contractions in bullfrogs prior to hypobaric decompressions (12) were associated with bubble formation in the resting animals while at altitude, and has been known since the early 1940s. The number of bubbles was reduced if the frogs were allowed to recover as long as one hr after electrical stimulations. The authors offered two explanations: a short-lived local increase in carbon dioxide that facilitated bubble growth at altitude, or the inception of micronuclei or some other short-lived entity that would later facilitate the growth of bubbles at altitude. This same concept was recently tested in humans (13) where twenty subjects were exposed to 6.2 psia on three separate and random occasions without the confounding of prebreathe or any exercise at altitude during a two hr exposure. Each subject did 150 deep knee bends in a period of ten mins either two hrs, one hr, or just prior to ascent with the remaining time spent adynamic in a chair. As with the frogs, it was hypothesized that exercise before decompression would generate a population of some entity (micronuclei, macronuclei, vapor-filled cavities trapped on vascular endothelium, or increase the concentration of carbon dioxide) that would diminish in size or concentration given enough time prior to ascent. They used subsequent VGE information to indirectly test the hypothesis. They observed that intense lower body activity just prior to the altitude exposure did cause more VGE to appear, and to appear earlier compared to when exercise was done earlier. The critical observation was that the predisposing factor(s) diminished with time while sitting quietly in a chair prior to the ascent.

The predisposing factors are assumed absent or reduced for EVAs in μg, but are assumed present for EVAs on the Moon or Mars.

LBA to reduce the risk of DCS, possibly by reducing the number and size of micronuclei, may have a limited utility in many situations but is important when relating DCS and VGE results obtained in altitude chambers to astronauts during EVA in μg. Astronauts do not move the lower body the same in space as they do on Earth. They are generally adynamic for several days prior to and during a space EVA. Indirect evidence suggests that astronauts and cosmonauts may have benefited from LBA since there has never been a report of DCS during an EVA. We acknowledge that underreporting can be attributed to additional factors that mask a minor pain-only symptom while in a space suit. Also, a bias, though denied, not to report any problems in an operational setting should be acknowledged, and is a constant concern to Flight Surgeons (14).

It is not possible to logically characterize an astronaut on the surface of the Moon or Mars as being adynamic even if the gravity is just 1/6th Earth-equivalent on the Moon and 3/8th on Mars. An astronaut in a Moon or Mars habitat would experience significant physical activity in the legs and would not unload all the forces in the lower body while ambulating on the surface. The additional risk of DCS and VGE from “Moon Loping” as compared to normal walking is unknown.

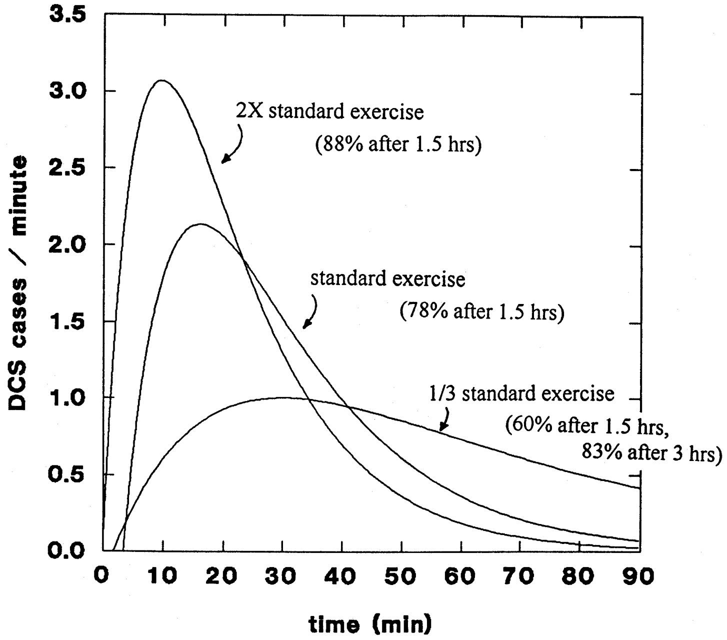

Figure 1. The rate of DCS as a result of exercise after an ascent to 3.0 psia without prebreathing. Standard exercise was 10 step-ups on a nine inch stool in 30 sec, repeated at 5 min intervals. Figure modified from Henry, 1956.

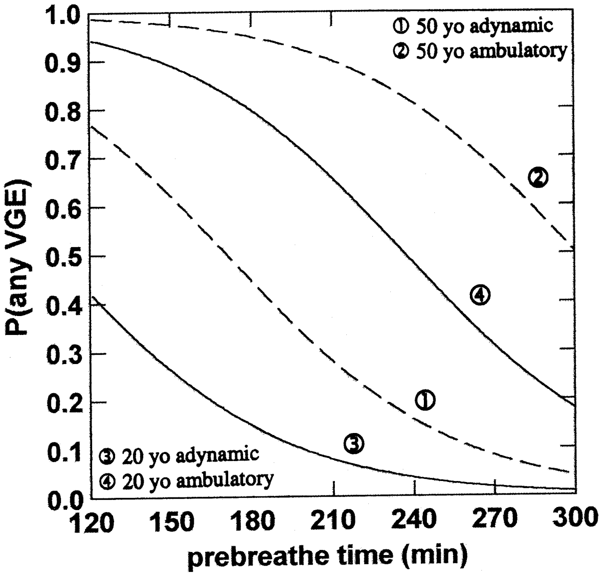

Figure 2. The probability of any Grade of VGE versus the PB time on 100% O_2 under four simulated conditions: ① with a 50 yo adynamic subject, ② with a 50 yo ambulatory subject, ③ with a 20 yo adynamic subject, and ④ with a 20 yo ambulatory subject, all with ascent to 4.3 psia and with light upper and lower body exercise as part of the exposure. Figure from Conkin et al, 2003.

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Appendix E-2:

Optimal Total Pressure-Oxygen Concentration Levels for Future Spacecraft, Spacesuits, and Habitats

Authors: Richard A. Scheuring, DO, MS, UTMB/Wyle Laboratories,
Johnny Conkin, PhD, NASA/JSC, Jeff Jones, MD, NASA/JSC, Mike Gernhardt, PhD, NASA/JSC

Introduction

This paper describes proposed environmental atmospheres for future long duration spacecraft, spacesuits, lunar and Mars habitats. Several atmospheric design points for the Constellation missions have been developed by the Environmental Atmosphere Working Group (EAWG) ranging from normoxic to moderately hypoxic while simultaneously hypobaric. These environments were analyzed to achieve a balance among the risk of decompression sickness, the overhead required to perform an exploration extravehicular activity (EVA), short and long term human performance at less than normoxic levels of partial pressure of oxygen (ppO_2), and the fire hazard. Atmospheres in future vehicles for exploration missions will likely be less than standard atmospheric pressure, with an ambient inspired ppO_2 less than a Earth sea level equivalent of 3.07 pound per square inch absolute (psia), or 159 mmHg. A hypobaric and reduced oxygen environment will be the integrated solution to safety, engineering, operational, and medical concerns that have as their goal routine and safe exploration of the Lunar or Martian surface. Indeed, the Constellation program goals and proposed mission architecture emphasize EVA with exploration of planetary surfaces as the central driving operation. However, there are important limits posed by human physiology, materials, and equipment factors (e.g. hematological and circulatory changes, flammability of materials, thermal performance of equipment within the vehicle and habitat) that must be considered when choosing these atmospheric parameters.

Assumptions

Crewmembers will have been pre-screened for blunted respiratory response to hypoxia.[13,16,20,25,34] Additionally, efficient and frequent EVA's drive the exploration initiative; low pressure EVA suit operations are preferred to high pressure suit ops to improve capability; there is an operational value to a short in-suit prebreathe; vehicle atmosphere composition may not mitigate the risk of decompression sickness (DCS) during an EVA; dedicated hyperbaric treatment capability may not be present on the vehicle or habitat,[9] and the vehicle and habitat materials have been certified for in-flight use in reduced oxygen partial pressure in microgravity. Finally, the alveolar partial pressure of oxygen (P_AO_2) is not directly measured in crewmembers. It is therefore assumed the ppO_2 correlates with the P_AO_2 based on established respiratory gas pressures and gas exchange ratio tables in the diving and aviation literature.[11]

Unknowns

There are several unknowns that exist when considering exposing humans to a chronic mildly hypobaric/hypoxic environment. There may be a synergistic effect between mild hypoxia and chronic microgravity exposure that alters blood rheology.[15,26,27,29] Will the proposed transition rate from launch to en route cabin atmosphere avoid acute physiologic effects? Likewise, will the transition to Mars atmospheric parameters be tolerated without adverse events? Immune function is known to be altered in microgravity and in non-spaceflight stressors such as hypoxia.[31,32] What are the implications for wound healing, infection resistance and reactivation of latent virus in the proposed hypobaric/mildly hypoxic environment? The proposed mission profile will demand frequent EVAs; how will the repetitive exposure to alterations in cabin and EVA suit environmental atmospheres (pressure and oxygen tension changes) impact cellular physiology?

Lastly, inherent environmental atmospheric sensor errors exist. Determining the actual environmental atmosphere, as opposed to the *indicated* pressure and oxygen concentration, may be difficult. How will these unknowns influence the final choice of environmental atmospheric parameters?

Background

The EAWG initially offered nine environmental atmosphere design candidates for consideration for the crew exploration vehicle (CEV) and lunar habitat (Table 1), with design point 9 ranking as the most preferred.[5] Operating at a cabin pressure of 8.3 psia and ppO_2 of 3.0 psia (155 mmHg), the ppO_2 altitude equivalent was approximately 1,600 feet above sea level. However, this design point approaches the existing materials flammability qualification envelope.[24] The authors of this flammability study stated that it is possible to operate safely in a cabin O_2 concentration of 36%, especially if helium is added as a diluent. Historically, much higher oxygen concentrations were used for the Apollo missions (cabin pressure 5.0 psia @ 100% O_2) and Skylab (cabin pressure 5.0 psia @ 70% O_2) (Figure 1). Interestingly, the available materials that were nonflammable in this environment were severely restricted, including crew clothing and packaging foams.[4] Usable materials were generally metallic in nature. In the present day, modification of available off-the-shelf hardware for safe use in the 70-100% O_2 environment is difficult and costly unless it is provided in a metallic case.[24]

The materials used on earlier missions were flame resistant but heavy. However, a key driver in developing the exploration vehicles will be to reduce mass and stowage volume. In addition to materials flammability and mass concerns, there are physiologic consequences of long term exposure to elevated oxygen levels (greater than 400 mmHg or 7.72 mmHg), or hyperoxic conditions.[11] Limits on exposure to hyperoxic environments is aimed at preventing oxidative stress on the organ systems of the crew. With higher levels of oxygen concentration, there is potential for progressive oxygen toxicity sustained mainly in the pulmonary system, but also possible in the nervous system, if under hyperbaric conditions (greater than 14 days at fraction of inspired oxygen concentrations (FiO_2) above 178 mmHg (3.44 psia).[23,33] The current Constellation environmental atmosphere design points do not approach these higher oxygen exposure limits.

Pt. No.	**Cabin Pressure, kPa (psia)**	**Cabin ppO_2, kPa(psia)**	**Cabin Oxygen, volume%**	**EVA Suit Pressure, kPa (psia)**	**P(DCS)**	**General Characteristics**
1	65 (9.4)	18.5(2.7)	28.5	29.6 (4.3)	0.089	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)	17.1(2.5)	26.8	29.6 (4.3)	0.094	Lowest cabin oxygen concentration with current space suit pressure; at hypoxic boundary.
3	73 (10.6)	16.9(2.5)	23.2	34.5 (5.0)	0.089	Moderate increase in space suit pressure with lower cabin oxygen concentration; at hypoxic boundary.
4	80 (11.6)	16.8(2.4)	21	41.4 (6.0)	0.038	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.

Pt. No.	Cabin Pressure, kPa (psia)	Cabin ppO_2, kPa(psia)	Cabin Oxygen, volume%	EVA Suit Pressure, kPa (psia)	P(DCS)	General Characteristics
5	88.5 (12.8)	18.6(2.7)	21	41.4 (6.0)	0.089	Higher space suit pressure with Earth-normal cabin oxygen concentration; well above hypoxic boundary. Ground testing may be facilitated.
6	91.0 (13.2)	21.0(3.0)	23.1	41.4 (6.0)	0.089	Higher space suit pressure. Normoxic cabin atmosphere; slightly elevated oxygen concentration.
7	70.3 (10.2)	18.6(2.7)	26.5	29.6 (4.3)	0.178	Current space suit pressure. This point represents shuttle EVA preparation conditions.
8	65.5 (9.5)	19.7(2.9)	30	29.6 (4.3)	0.079	Current space suit pressure with assumed maximum oxygen concentration from the pressure study. O_2 concentration control limits may be outside of existing materials flammability qualification envelope.
9	57.2 (8.3)	20.6(3.0)	36	29.6 (4.3)	0.011	Current space suit pressure. Highest oxygen concentration point (above that assumed in the pressure study) and lowest cabin pressure minimize prebreathe time. Outside of existing materials flammability qualification envelope.

Table 1. EAWG Design Candidates. (Campbell PD, Henninger D. EAWG Results to Date. EAWG Atmospheres Workshop, November 2005)

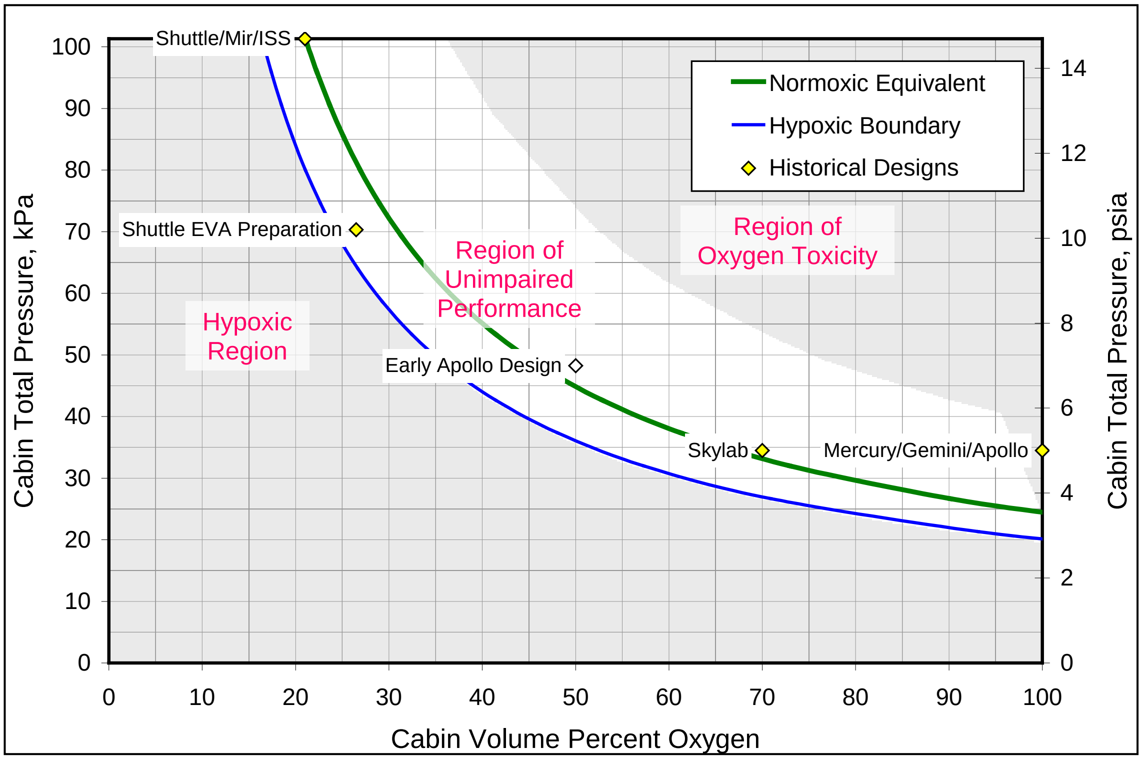


Figure 1. Historical Spacecraft and Current Shuttle/ISS Cabin and Suit Atmospheres (Adapted from Henninger D, Campbell PD. Briefing to SLSD on EAWG Recommendations, December, 2005.NASA/JSC Bioastronautics Exploration Research and Technology Office)

In contrast to the normoxic or hyperoxic environmental atmosphere proposals, mild to moderately hypoxic and hypobaric scenarios, equivalent to 6,000 to 8,000 feet above sea level, have been suggested for consideration.[4,5,7] The advantage of this hypoxic/hypobaric environment has been identified as decreased DCS risk, reduced oxygen pre-breathe time and lower suit pressure for improved mobility and dexterity.[5,9,14] More recently, the EAWG has proposed an operational environmental altitude equivalent to 3,500 feet above sea level.[6] The spaceflight and surface operations EVA suits recommendation is consistent with current Shuttle/ISS suit atmosphere of 4.3 psia @ 100% O_2. Other recommendations for long-duration outpost habitats on planetary surfaces expose the crews to 8.0 psia @ 32% O_2 and 7.6 psia, 32% O_2 (altitude equivalents between 5,000 and 6,500 feet, respectively) (Table 2).

Vehicle	**Nominal Total Pressure (psia +/- 0.2 psia)[4]**	**Nominal Oxygen Partial Pressure (mmHg) [4]**	**Nominal Oxygen Concentration (% +/- 2.0 percentage points)[4]**	**Range of Total Pressure Capability (psia) [1]**	**Tissue Ratio (R) After 60 Minutes Prebreathing[3]**
CEV to ISS	14.7 10.2[5]	160 (0 ft) 140 (3500 ft)	21 26.5	0-14.9	
CEV In-Space Suit	4.3	222	100	4.0-4.6	1.55 from 10.2 psia CEV to 4.3 psia suit
Lunar and Mars CEV	14.7 10.2	160 (0 ft) 140 (3500 ft)	21 26.5	0-14.9	
Lunar and Mars Landers	10.2 8.0	140 (3500 ft) 132 (5000 ft)	26.5 32	0-14.9	
Lunar and Mars Surface Suits	4.3 6.0	222 310	100 100	3.5-8.0 [2]	1.13 from 8.0 psia Landers to 4.3 psia suit; 1.07 from 7.6 psia Surface Habitats to 4.3 psia suit
Lunar and Mars Surface Habitats	8.0 7.6	132 (5000 ft) 126 (6500 ft)	32 32	0-14.9	
Mars Transit	14.7 10.2	160 (0 ft) 140 (3500 ft)	21 26.5	0-14.9	

Table 2. Summary of Recommendations for Constellation Mission Systems

Note 1: Range of total pressure capability covers Earth launch, Earth entry, and contingencies.
Note 2: Surface suit 3.5 psia capability for suit emergency operations, 8.0 psia for DCS treatment.
Note 3: 60 minute in-suit prebreathe is defined as the time in the suit after purge and leak check until absolute pressure on the body reaches 4.3 psia after a nominal depressurization.
Note 4: All nominal values are centers of control boxes assumed +/-0.2 psia total pressure, +/-2 percentage points oxygen.
Note 5: 10.2 psia recommendation is based on Shuttle experience, for CEV contingency EVA preparation.

Methods

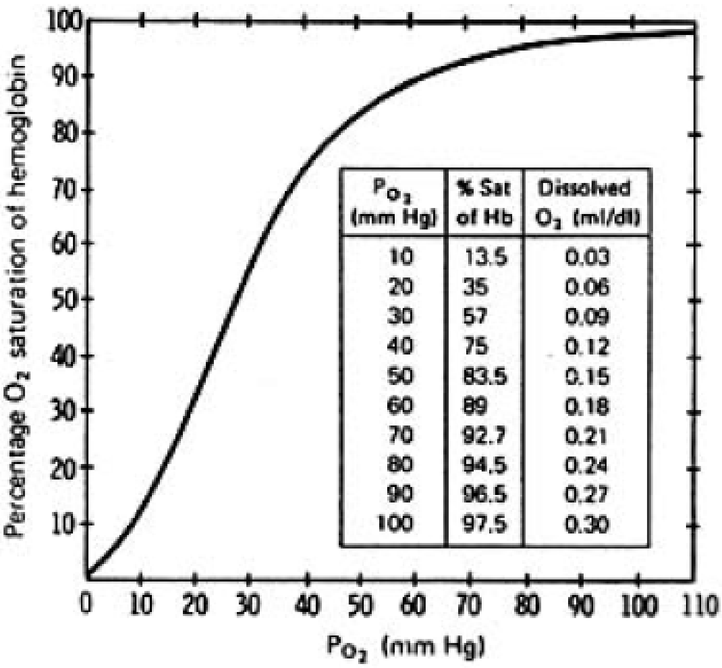
An extensive review of the current database of altitude physiology, alterations in physiology occurring with exposure to microgravity, characteristics of materials exposed to various environmental atmosphere conditions, and prior spaceflight mission technical reports was conducted. Appropriate charts, graphs and observations were extracted from studies and tests relevant to the operational environments anticipated for exploration missions, and many are included in this paper.

Results

The proposed spacecraft and habitat environmental atmosphere take into the account the following:

Crewmember Physiology

Under standard atmospheric conditions of 14.7 psia pressure and ppO_2 3.0 psia (159 mmHg), approximately 98% of the hemoglobin will be saturated with oxygen during passage through pulmonary capillaries. This is reflected in the oxygen-hemoglobin dissociation curve when the P_AO_2 is 100 mmHg (Figure 2). The P_AO_2 takes into consideration the dilutional effects of water vapor and carbon dioxide at the level of the alveoli, hence the lower value.



P_{O_2} (mm Hg)	% Sat of Hb	Dissolved O_2 (ml/dl)
10	13.5	0.03
20	35	0.06
30	57	0.09
40	75	0.12
50	83.5	0.15
60	89	0.18
70	92.7	0.21
80	94.5	0.24
90	96.5	0.27
100	97.5	0.30

Figure 2. The normal oxygen-hemoglobin dissociation curve. (Guyton AC, Hall JE. Textbook of Medical Physiology, 10th Ed. WB Saunders: Philadelphia, 2000, p. 466-467.)

The oxyhemoglobin dissociation curve describes the relationship between the P_AO_2 (x-axis) and the oxygen saturation (SaO_2) (y-axis). Hemoglobin’s affinity for oxygen increases as successive molecules of O_2 bind, with a greater number of O_2 binding as the P_AO_2 increases until the maximum amount that can be bound is reached. At a P_AO_2 above 60 mmHg, the standard dissociation curve is relatively flat. Conversely, below a P_AO_2 of 60mmHg, the hemoglobin's affinity of O_2 diminishes, allowing O_2 to be unloaded to the peripheral tissues.[17] This accounts for the sigmoidal shape of the curve. Technically, as the P_AO_2 falls below 100 mmHg (1.93 psia) the hemoglobin begins to desaturate, resulting in a relative "hypoxic" zone. Clinically, symptoms of hypoxia are not observed in healthy individuals until the P_AO_2 enters the steep portion of the curve, generally below 60 mmHg (1.16 psia) corresponding to a hemoglobin saturation of less than 90%. This corresponds to an equivalent altitude in non-acclimatized individuals of greater than 10,000 ft above sea level[11,17] Interestingly, the amount of alveolar carbon dioxide, P_ACO_2, and water vapor pressure change little at this altitude, adding to the dilutional effects. Reduced atmospheric pressure with concomitant reduction in P_AO_2 below 60 mmHg has several acute effects (Figure 3), including decreased mental proficiency, visual acuity, muscle fatigue, nausea, headache, and impaired discrete motor movements. [11,15,17]

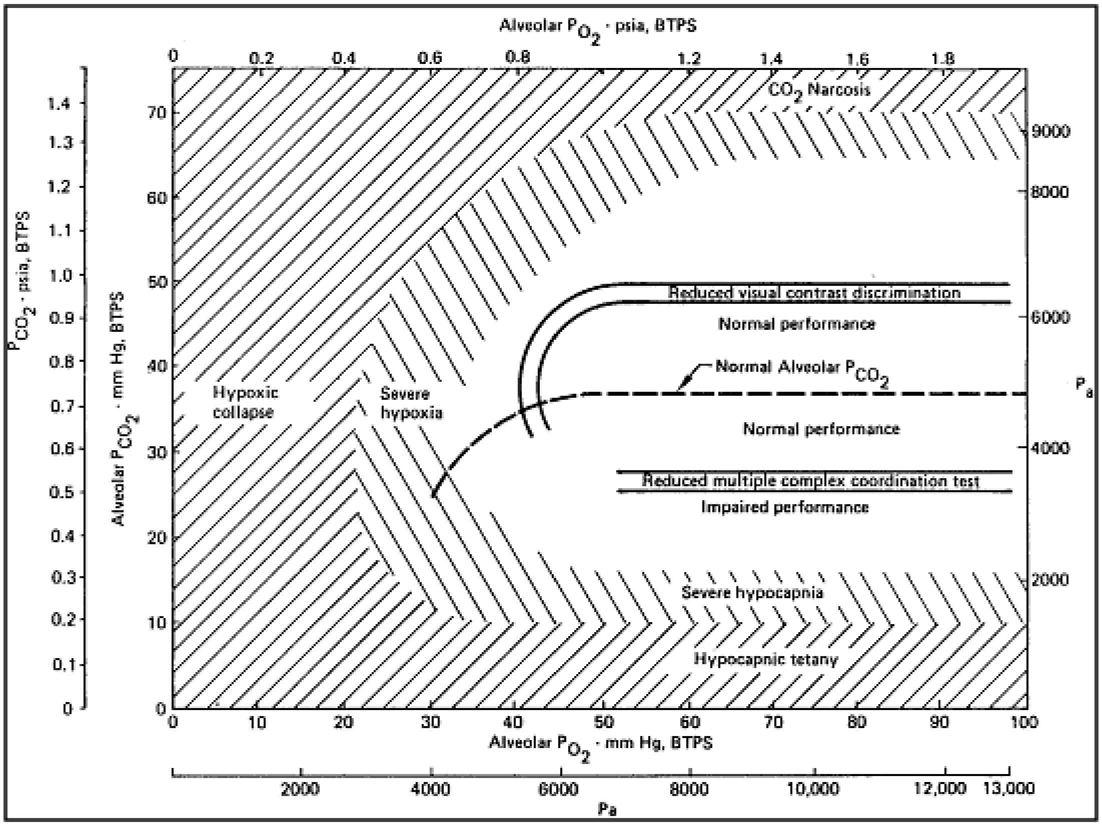


Figure 3. Relationship of Alveolar O_2 and CO_2 Composition to Performance. (NASA STD-3000 58)

Prolonged human exposure to reduced oxygen tension usually results in the induction of adaptive changes. The most dramatic evidence of adaptation to hypoxic conditions is observed in the changes in blood viscosity. Prolonged non-lethal hypoxia results in increases in the total blood volume and oxygen carrying capacity of the blood. The hematocrit may rise from a normal value of 40 to 45 in an average male up to 60, over the period of 4 weeks, with a concomitant increase of 20 to 30 % in the blood volume.[11,17,28]

Adaptation to microgravity has hematologic effects that interact negatively with the adaptations to hypoxia. Reductions in total blood volume (TBV) have been noted since the early Gemini and Apollo while working in a hyperoxic (ppO_2 5.0 psia/259 mmHg) environment.[19] These findings were observed in crewmembers during the Skylab missions (ppO_2 2.54 psia/127 mmHg) as well, averaging reductions in TBV by 13% on average.[19] Skylab crewmembers also experienced a 7%-14% decrease in their red blood cell volume (RBV). Although red blood cell count and TBV both decrease in chronic microgravity, the hematocrit (RBV/TBV) remains near preflight levels. The change in RBV is believed to be linked to changes in erythropoietin (EPO) secretion by the kidneys. EPO is typically secreted to stimulate RBC production in response to reduced arterial PO_2.[1,4,11,17] However, with the loss of plasma volume (up to 27% less/kg body mass (ml/kg))[29] encountered initially in microgravity, the kidneys may suppress EPO production as the blood viscosity increases. Also, the need for oxygen carrying capacity is reduced as lower extremity muscles become inactive and lose mass. Additionally, a small amount of circulating RBC mass is lost initially in microgravity due to neocytolysis.[1] Neocytolysis refers to the observed decrease in RBC mass due to destruction of RBCs either newly released or scheduled to be released from the bone marrow.

So there may be two conflicting processes going on simultaneously during exploration transit phases: a normoxic or mildly hypoxic atmosphere causing the synergistic effects of reduced ppO_2 and subsequent increased oxygen carrying capacity in the blood by increasing RBC production vs. the commonly observed effects of plasma loss and RBV loss in response to microgravity. Which process predominates? In an attempt to understand the possible physiological interaction of hypoxia and microgravity, researchers at NASA Glenn Research Center analyzed existing data assuming a long duration mission in mildly hypoxic conditions, equivalent to 5,000-8,000 ft.[15] Observations made from the data (Table 2) reveal that relatively little change occurs in blood viscosity between 0-5,000 ft. However, the blood viscosity increases between 15-50% when crew members have been exposed to microgravity at altitudes of 8,000 ft. The authors concluded that the combination of hemoconcentration from PV loss and increased RBV result in increased blood viscosity. The clinical concern is that increased blood viscosity, in the setting of reduced circulation in the lower extremities and overall reduced venous system tone, may increase the risk of cardiovascular events, such as thrombi formation.[15,27,29]

Atm Equivalent Altitude (ft)	Change in PV (ml)	Total PV (ml)	Change in RBV (ml)	Total RBV (ml)	TBV (ml)	Hematocrit (%)	*Relative Viscosity
0-5000	0	2764	0	1824	4588	40	4
6000	-91	2673	170	1994	4667	43	4.6
7000	-183	2581	340	2164	4745	46	5.3
8000	-274	2490	509	2333	4823	48	6

*Relative Viscosity is defined as the blood's viscosity relative to that of water at 37°C.

Table 2. Estimated changes in blood volume components and hematocrit based on the case of long duration exposure (chronic conditions) to both microgravity and mildly hypoxic atmospheric conditions. Note that an average body mass of 68.2 kg was assumed to conform to Skylab 4 astronaut conditions on return (R+0). (Courtesy of Griffin DW, Meyers JG. Biomedical Effects of Proposed CEV Atmospheres. NASA Glenn Research Center, 2005)

However, there have been no observed or reported episodes of thrombus or embolus in either animals or humans during short or long duration spaceflight, so this concern may be only theoretical. This observation is consistent with periodic health assessment information from ISS: after the initial period of hemoconcentration that occurs during early microgravity exposure (adapting to fluid shifts and subsequent diuresis), the hematocrit normalizes (ISS crew at ppO_2 of 145-170 mmHg) and stays in the low normal range throughout the remainder of the mission. One means to reduce the perceived risk associated with this uncertainty is to operate the vehicle atmosphere within our existing microgravity experience base during the microgravity transit phase, then transition toward the lower habitat pressures and ppO_2 levels gradually. Gravity in lunar and Mars missions and its effects on pulmonary and cardiovascular physiology is another consideration, although it is not likely to have physiological significance. In summary, the lunar missions will serve to build our experience base prior to conducting the longer duration Mars missions.

Launch to En Route Cabin Pressure and Oxygen Concentration Changes

The proposed atmospheric transition after launch is displayed graphically in figure 4. The transition from sea level atmospheric pressure and oxygen concentration (14.7 psia and 21% O_2) to an en route cabin pressure and oxygen concentration range of 10.2 psia and 26.5% O_2 (3,500 ft) to 8.0 psia and 32% O_2 (5,000 ft) would likely use procedures similar to those currently practiced on shuttle and ISS missions. The launch cabin pressure would be staged down initially to ~10.2 psia and the O_2 enriched to ~26.5% consistent with existing shuttle and station flight rules.[23] If it was desired to reduce the ppO_2 to lower levels to provide for a slow acclimatization to the Lander and Habitat ppO_2 (~ 2.56 psi), then it should be relatively straight forward to breath down the oxygen gradually over time consistent with some TBD acclimatization protocol. During the lander/CEV docked operations the cabin pressure and F_iO_2 would be consistent with the CEV limitations on O_2 concentration (< 30%). Once the crew had transferred into the Lander and undocked from the CEV, the cabin pressure could be further reduced and the O_2 concentration would be elevated to 32%. There is no physiological time constraints to when this depress could occur. Consequently, there is little risk of DCS associated with this pressure transition as it is below the threshold for tissue supersaturation.

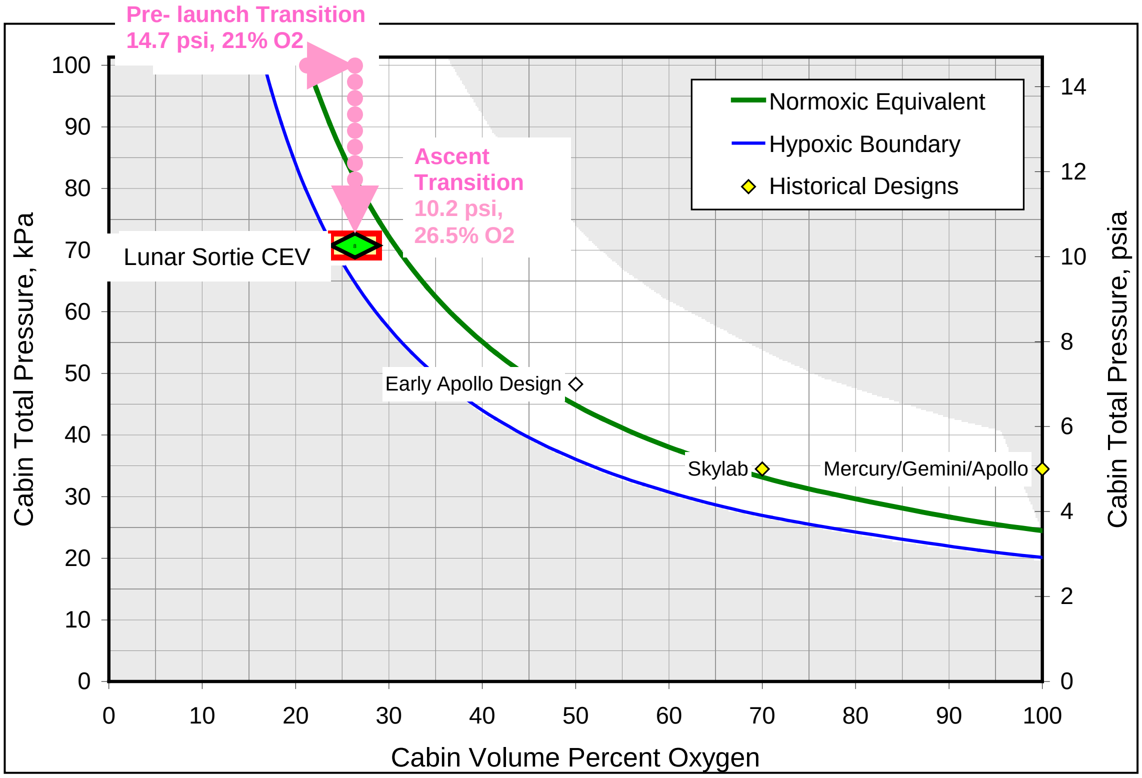


Figure 4. Concept for Lunar-Mars CEV Atmosphere Transition on Earth Ascent. (Adapted from Henninger D, Campbell PD. Briefing to SLSD on EAWG Recommendations, January, 2006.NASA/JSC Bioastronautics Exploration Research and Technology Office)

This approach is consistent with the observation that the hypoxic ventilatory response (HVR), which is the increase in ventilation brought about by hypoxia, takes place over a period of days.[34] This is shown by an increase in ventilation and a decrease in P_ACO_2 (Figure 5). Why is this important to consider with respect to determining the transition rate from sea level to mildly hypoxic/hypobaric cabin atmosphere? The terrestrial analog to the clinical changes that occur in response to acute exposure to an increase in cabin altitude is acute mountain sickness (AMS), a condition affecting otherwise fit people on ascending rapidly to altitude. Symptoms of AMS include breathlessness, headache, nausea, vomiting, disturbed sleep and poor physical performance.[26,34] It is important to point out that this increase in ventilation varies greatly among individuals, and does not usually begin until the inspired PO_2 is reduced to approximately 90 mmHg (1.71 psia), an altitude equivalent of 10,163 ft above sea level, but can occur at lower levels/altitude equivalents in susceptible individuals. This limit is also imposed on pilots operating in commercial airlines and military flight operations.[7,12] In summary, ranges of time must be considered in altitude transition effects, and both acute and chronic acclimatization. The Figure below shows the difficulty of giving a specific answer to the question of “how long does it take to acclimate to a reduced-oxygen condition?”

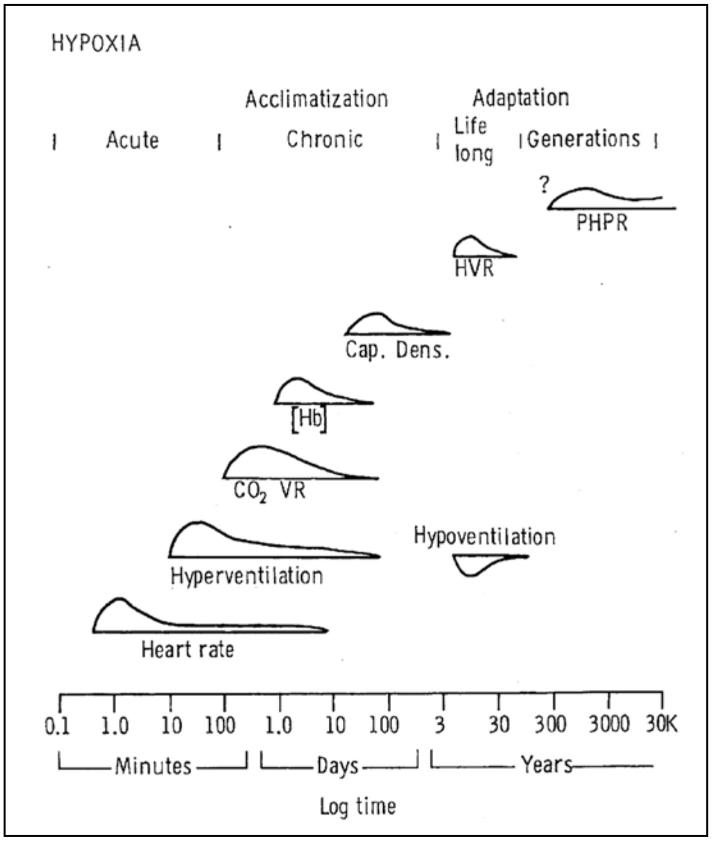


Figure 5. Time courses of a number of acclimatization and adaptive changes plotted on a long time-scale, the curve of each response denoting the rate of change, fast at first then tailing off. Included are: heart rate, hyper and hypoventilation, the CO_2 ventilatory response (CO_2VR), hemoglobin concentration ([Hb]), changes in capillary density (Cap. Dens), hypoxic ventilatory response (HVR) and the pulmonary hypoxic pressor response (PHPR). (Adapted from Ward MP, Milledge JS, West JB. High Altitude Medicine and Physiology. University of Pennsylvania Press, Philadelphia, 1989, pgs. 67-96)

Risk of Decompression Sickness

Decompression sickness is a potentially debilitating and life-threatening condition that occurs when inert gas, typically N_2, evolves out of the blood and body tissues. The evolved gas can compress nocioceptive tissues causing pain (“the bends”), or interrupt venous or arterial blood flow, or other vascular and neurological disorders.[3,11] An individual is at risk of developing DCS whenever exposed to an ambient pressure lower than the tissue nitrogen tension. In order to estimate the severity of DCS, the tissue ratio, or R-value, *R*, was developed. The R-value is defined as the ratio of the tissue nitrogen tension in 360 minute half-time tissue before depressurization to the ambient pressure after depressurization:

$$R = \frac{P_{N2\text{-}Tissue}}{P_{Suit}}$$

In general, the higher the *R*-value above 1.0, the greater the likelihood of DCS.[4,21] However, a number of other variables influence the likelihood of developing DCS, including the time the individual is exposed to reduced pressure, the degree of physical activity, the ambulation contact forces at reduced pressure, the pressure profile, repeated exposure to hypobaric pressures etc.[9] To reduce the risk of DCS when transitioning from the cabin atmosphere to the EVA suit environment, crewmembers are exposed to 100% O_2 for varying periods of time in an attempt to "washout" N_2 from the body tissue. These procedures reduce but do not entirely eliminate N_2 from the tissues, but do reduce the EVA crewmembers' *R*-value at the time of decompression to the lower EVA suit pressure. The current shuttle and ISS EVA suit operates at a suit pressure of 4.3 psia for maximum mobility and reduction of crewmember fatigue. It is assumed that planetary EVA suits will operate at pressures near 4.3 psia.

For the proposed habitat cabin atmospheric pressure of 8.0 psia (414.5 mmHg) at 32% ppO_2, the ppN_2 is 5.43 psia (281.9 mmHg). The *R*-value without additional in-suit prebreathe at a suit pressure of 4.3 psia is:

$$R = \frac{5.43}{4.3} = 1.23$$

The *R*-value, after a proposed maximum acceptable 60 minute in-suit 100% oxygen prebreathe, is calculated as:

$$R = \frac{4.86}{4.3} = 1.13$$

Reducing In-suit Prebreathe Time by Living in a Hypobaric and Mild Hypoxic Environment
At this time an acceptable R-value for exploration EVA's has not been determined. That determination will be made as part of an integrated approach that would first define the acceptable decompression risk for different phases of the mission (The Exploration DCS Risk Definition and Contingency Plan). The prebreathe verification tests would be conducted using an EVA simulation that is appropriate with respect to metabolic rates, time, and ambulation contact forces. In general, for a given suit pressure, the amount of prebreathe time required for a given R-value will be reduced by reducing the nitrogen partial pressure in the habitat or lander. Prebreathe time could be completely eliminated if the habitat atmosphere was 100% O_2. However, a balance must be achieved between the increased risk of fire at high O_2 concentration and the decreased risk of DCS as N_2 pressure in the habitat is reduced. The concentration of O_2 and therefore risk of fire for a given total pressure can be slightly reduced if mild hypoxia is accepted. The degree of hypoxia anticipated is equivalent to living in Denver Colorado, or Albuquerque New Mexico, at about 5,280-6000 feet altitude.

Even small reductions in the nitrogen partial pressure of the habitat can result in significant reduction in prebreathe time. To illustrate this point we compare the prebreathe times required to achieve different R-values from different CEV and habitat atmosphere options:

I. 10.2 psia @ 26.5% O_2 with a 60 minute in-suit prebreathe to achieve an R-value of 1.55 for contingency EVAs from the Crew Exploration Vehicle (CEV). This is a hypobaric and mildly reduced-oxygen environment, equivalent to breathing air at 3,500 feet altitude. To achieve the same R-value as the lower habitat pressures in option II and III would require 224 and 252 minutes, respectively.

II. 8.0 psia @ 32.0% O_2 with a 60 minute in-suit prebreathe to achieve an R-value of 1.13 for lunar EVAs. This is a hypobaric and mildly reduced-oxygen environment, equivalent to breathing air at 5,000 feet altitude.

III. 7.6 psia @ 32.0% O_2 with a 60 minute in-suit prebreathe to achieve an R-value of 1.07 for Mars EVAs. This is a hypobaric and mildly reduced-oxygen environment, equivalent to breathing air at 6,500 feet altitude.

Whereas the specific acceptable R-value for exploration EVAs has yet to be determined, it is clear that reduction in habitat nitrogen partial pressure will result in a significant reduction in prebreathe time.

Environmental Atmosphere Sensor Error

The environmental control and life support system (ECLSS) group has determined that environmental sensor error exists in measuring both total cabin pressure and oxygen concentration. The ECLSS community estimates that a +/- 0.2 psia error exists in measuring the total atmospheric pressure and +/- 2% error in measuring O_2 concentration (Figure 6). However, we would anticipate improved sensor capability in future vehicles.

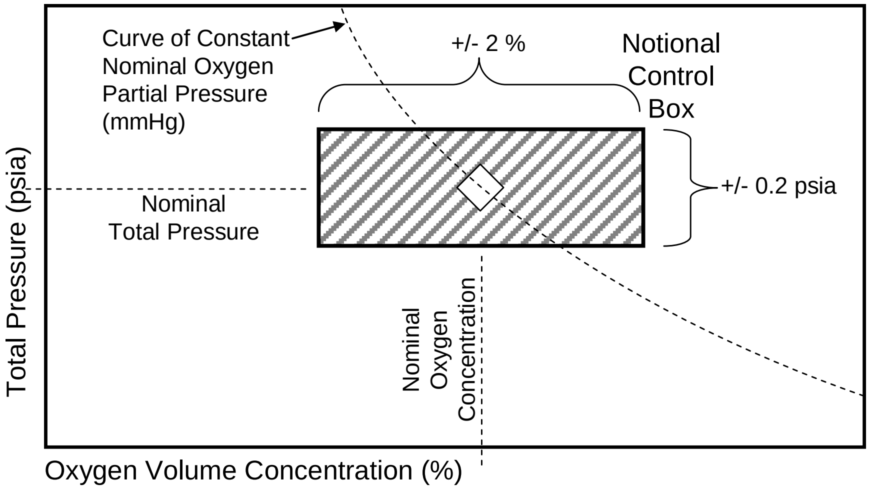


Figure 6. Notional Control Box for Vehicle Cabin Atmospheres. (Adapted from Henninger D, Campbell PD. Briefing to SLSD on EAWG Recommendations, December, 2005.NASA/JSC Bioastronautics Exploration Research and Technology Office)

Discussion

Humans adapt to hypoxic exposure over a period of days to weeks (45-60 days) by increasing minute ventilation, splenic contraction, redistribution and increase in circulating blood volume, augmenting the oxygen carrying capacity of the blood.[26,27,34] The proposed mission transitions the vehicle atmospheric profile from a launch atmosphere of 14.7 psia and 21% O_2 to a CEV atmosphere of 10.2 @ 26.5% O_2 over a period of a couple days. The en route to surface cabin pressure would be further reduced to 8.0psia @ 32% O_2. The corresponding launch P_AO_2 (103 mmHg or 1.98 psia) to CEV (86 mmHg or 1.65 psia) and surface P_AO_2 (81 mmHg or 1.56 psia) represents an altitude equivalent of 3,500 ft to 5,000 ft., well within the acceptable physiological range. This statement is supported by work done with United States Air Force (USAF) pilots studied in mildly hypoxic environments (5,000 ft to 8,000 ft above sea level), with some limitations.[34] The authors measured cognitive performance (continuous performance tasks, grammatical reasoning, math processing, and spatial orientation tasks. Although the pilots reported subjective symptoms associated with acute hypoxic exposure there were no statistically significant changes in their cognitive performance below 8,000 ft. However, the hypoxia exposure was of short duration (hours) and limited to few objective physiological variables (SaO_2 and heart rate).

Figure 7 graphically represents the Constellation mission environmental atmospheres that have been proposed in this whitepaper contrasted with historic spacecraft atmospheres.

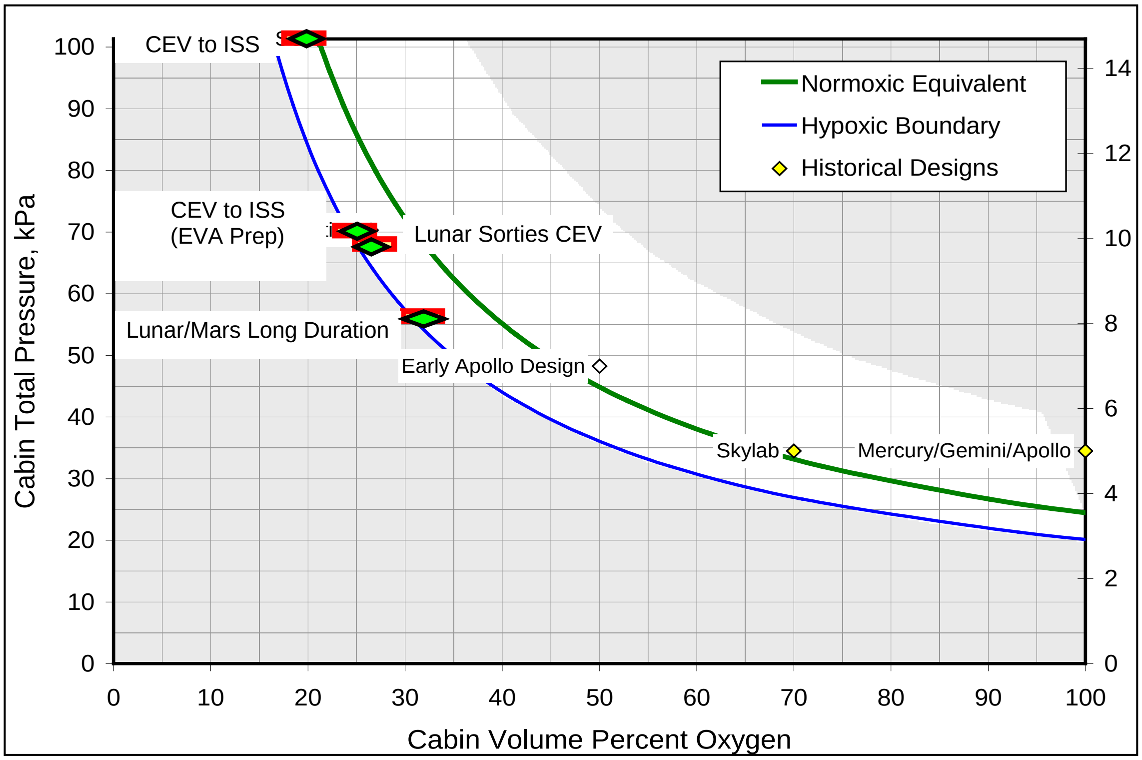


Figure 7. Historical Spacecraft and Recommended Constellation Atmospheres.
(Adapted from Henninger D, Campbell PD. Briefing to SLSD on EAWG Recommendations, December, 2005.NASA/JSC Bioastronautics Exploration Research and Technology Office)

One concern raised by a staged depressurization is that it will take approximately 36 hours to equilibrate at the LSAM habitat pressures, so the first EVAs from the LSAM (~12-24 hours after establishing the LSAM atmosphere) would require a slightly longer prebreathe as the crew will not be fully equilibrated at the reduced ppN_2. NASA's current prebreathe protocol testing would need to account for the details of this procedure. Interestingly, the historic atmospheric standard, contained in the NASA Human Integration Standards 3000 (HSIS) document for cabin atmospheric pressure is the range of 190 to 760 mmHg (3.6-14.7 psia). At pressures below 190 mmHg crews are required to don pressure suits and to breathe 100% oxygen. Crewmembers are not directed to don an O_2 mask in the current standard, as long as the vehicle cabin ppO_2 provides a P_AO_2 of at least 103mmHg (1.98 psia) which is sea level equivalent.[22] The current ISS flight rule defines the lower limit requiring supplemental oxygen as an inspired ppO_2 of 111 mmHg[23], [which results in a P_AO_2 of 62 mmHg (at e.g. 6.35 psia (329 mmHg)/34% O_2 ambient)], clearly below the current HSIS standard. The 10,000 ft. altitude equivalent (111 mmHg ppO_2) also represents the maximal altitude that DOD and commercial FAA pilots may fly without supplemental oxygen (accepted masking level).[7,12]

Although technically the crew member is initially mildly hypoxic, the SaO_2 is maintained over 94% at rest. The worst case scenario taking into consideration the environmental atmosphere sensor error of -0.2 psia and -2% O_2 concentration for the CEV and lunar habitat exposes the crewmember to a P_AO_2 of 73 mmHg (1.40 psia) and 65.3 mmHg (1.26 psia), respectively. As was stated earlier, desaturation of Hb occurs at a P_AO_2 <60 mmHg. Even in the worst case scenario for sensor error taken into consideration, the crew will not approach this level of hypoxia. After acclimatization, less impairment at rest would be expected.

Little consideration has been given to the effects of exercise in hypoxic environments to this point where high metabolic workloads are expected. While resting pulmonary blood flow may allow adequate time for equilibration of oxygenation of Hb during pulmonary transit time, exercise causes an attendant increase in cardiac output. In the hypoxic environment, this time is shortened, resulting in precipitous falls in SaO_2 secondary to the reduced capillary transit time. Although this is a valid concern, oxygen delivery to the tissues should not be compromised as exercise in the habitat will not exceed 30 minutes. However, studies will need to be performed to account for these hypoxic effects when developing exercise countermeasures for protecting aerobic fitness and bone loss mitigation. In regards to the EVA environment, it is important to point out that EVA with suit pressures above 3.7 psia with 100% O_2 are slightly hyperoxic. Therefore, performance limitations during EVA attributable to reduced O_2 availability would be not expected.

A similar concern for operating in the hypoxic range is raised in regards to reducing the margin of oxygen delivery to the crew during a contingency, such as fire or exposure to toxic chemicals (such as propellants and combustion products). Material flammability testing will need to confirm ignition characteristics in this environment. Also, regardless of the environmental oxygen concentration, a crew member will have supplemental oxygen supplied via the portable breathing apparatus (PBA) in the event of a toxic environmental exposure.

In reviewing the various proposed design points generated by the EAWG and others in the space engineering community it is tempting to push the physiological envelope to accept lower cabin pressures and ppO_2 levels. Indeed, some authors suggest that crewmembers exposed to moderately hypoxic conditions during long-duration missions should exhibit greater resistance to severe, acute hypoxia and DCS after a period of acclimatization.[30] However, it is important to note that although the 3,500 ft - 5,000 ft altitude equivalent is well within the operating envelope of physiological function, further compromise of the proposed cabin and suit atmosphere parameters may exceed the adaptive responses the body to hypoxia and microgravity (Figure 5).[9,11,15]

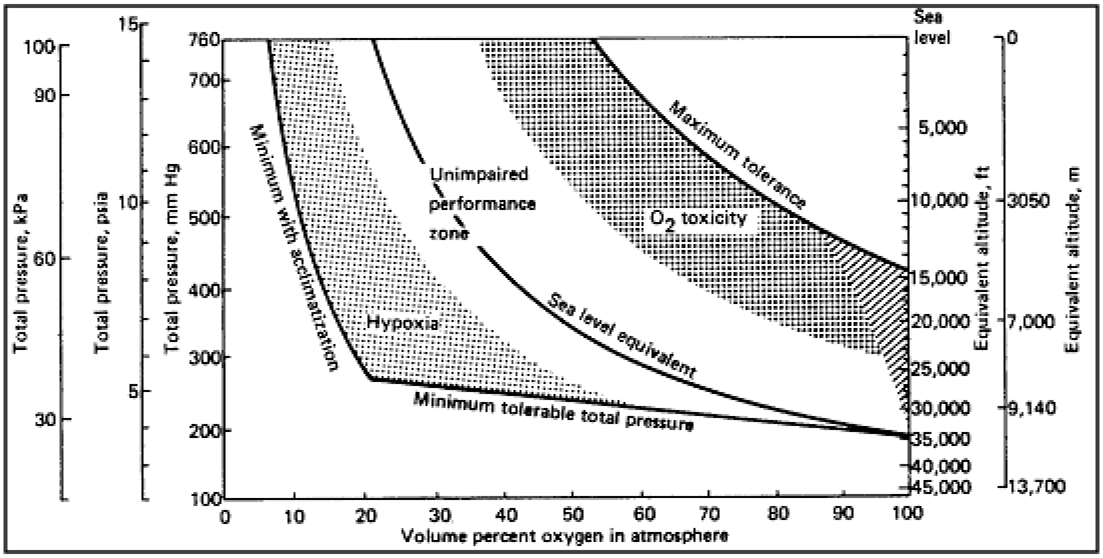


Figure 5. Total pressure versus percentage of oxygen and defined regions of hypoxia, normoxia, and hyperoxia. (NASA-STD-3000 56)

It is for this reason that we recommend conducting the microgravity portions of these short duration CEV to ISS and lunar transit missions within our existing space flight experience base. This would not result in any compromise to the capability of the CEV and LSAM to support safe and efficient EVA, and eliminates the need to conduct expensive and likely inconclusive ground studies on the combination of mild hypoxia and micro-gravity. The current NASA prebreathe protocols for the Space Shuttle and ISS are based on a final *R*-value of 1.65-1.68 after the O_2 prebreathe period.[22] Current model predictions suggest that having an *R*-value between 1.22 and 1.40 will significantly reduce the risk of DCS in crewmembers.[4,8]

The proposed *R*-value of 1.23 without an additional O_2 prebreathe period fits well within these recommendations. Reducing the partial pressure of N_2 in the habitat through a combination of reduced total pressure and increased O_2 concentration without incurring a significant hypoxic or fire risk results is a significant reduction in final in-suit prebreathe time to achieve a satisfactory R-value. The benefit of increased joint mobility while operating in the EVA suit will increase crewmember productivity and decrease fatigue. However, it is important to recognize that appropriate human ground trials will be required to validate any prebreathe protocols. Additionally, the long term microgravity exposures (Lunar surface operations, Mars transit, and Mars habitat) will require that data be collected to develop an operationally-focused research program consisting of: 1) validation of the proposed prebreathe protocols for exploration EVA operations, 2) extending the testing and certification of spaceflight materials to higher O_2 concentrations that envelope these habitat atmosphere recommendations, 3) validate food preparation strategies at the proposed pressures, and 4) reduce the uncertainties of the proposed atmospheric effects on blood rheology, immune function, and cellular physiology in response to repetitive atmospheric changes associated with EVA operations.

Conclusion

Recommendations

We have provided an evidence-based approach for selecting the optimal total pressure-oxygen concentration levels for future spacecraft and habitats. Careful consideration of the current evidence reveal crewmembers will have minimal detrimental physiological effects of mildly reduced oxygen partial pressure equivalent to 3,500 ft to 5,000 feet above Earth sea level. Mission efficiency can be significantly improved under these atmospheric parameters by reducing or eliminating the dedicated oxygen prebreathe by the EVA crew. Depending on the hypobaric and mild hypoxic conditions, there is a two to eight-fold reduction in the in-suit prebreathe time to achieve the stated R-values.

These recommendations are consistent with existing NASA Shuttle and ISS standards and flight rules for breathable atmosphere and oxygen concentration, so that the CEV and habitat can be designed with no new materials limitations. The short term CEV to ISS and lunar transit missions will stay within the known operational experience base and should not require any new Earth-based physiological testing for the combined effects of microgravity and hypoxia. However, the proposed lander and habitat recommendations will require that the current NASA Standard 3000 (HSIS) total pressure and oxygen concentration limits be amended to accommodate the new environmental atmosphere ranges. These recommendations will also require materials ignition and flammability testing and certification to 34% oxygen concentration. Data collected during lunar missions (with increasing duration) will be used to formulate the plan for Mars exploration, with the assumption that the physiological interactions of reduced gravity and lower oxygen tension will be diminished as the gravity level increases on the Martian surface relative to the Moon. Implementing these recommendations, in addition to bringing some new challenges, will provide significant improvements in operational productivity for planetary surface exploration.

Acknowledgements

The authors would like to thank David Gillis, MD, PhD at UTMB/Wyle laboratories for reviewing the physiological considerations of this whitepaper. Dr. Gillis provided valuable input from a clinical perspective based on his years of experience as a Naval flight surgeon and practicing anesthesiologist.

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Appendix F:

Exploration Atmospheres Workshop
November 1-3, 2005
Houston

1. Executive Summary

The Exploration Atmospheres Workshop was conducted to validate the Exploration Atmospheres Working Group's (EAWG) recommendations for human-occupied atmospheres and for additional research and technology development to enable NASA to specify exploration atmosphere requirements. Both NASA-affiliated and select external experts were in attendance to review the EAWG plans, process and analysis methods and results. A second goal for these participants was to provide recommendations concerning these review areas with respect to atmosphere design.

To structure the workshop discussion, eight questions were derived prior to the workshop that guided reviewer comments such that these objectives could be achieved within the timeframe of the workshop. Accordingly, alternate plenary and breakout sessions were arranged to discuss and evaluate the EAWG background material, technical white papers on major risks and analyses performed by the EAWG with respect to candidate atmosphere design points. The results of these sessions led to guided plenary discussions and two series of breakout reports, both of which are furnished in this report.

A key result of this process was the segmentation of suggested design atmosphere points by vehicle and mission class, including the Crew Exploration Vehicle (CEV), the lunar and Martian landers and habitats, and the Mars transit vehicle. Revised recommendations for oxygen partial pressure and total atmosphere pressure were developed during the workshop and proposed by the attending EAWG members for consideration as the formal recommendation of the working group.

A driving principle was developed by the combined group (EAWG members and reviewers) for selection of preferred design points for each mission. This principle emphasized the importance of facilitating surface extravehicular activities (EVA) by mitigating decompression sickness risk and by shortening the necessary pre-breathe protocol time, in order to enhance mission productivity (mitigating mission operations risk). The participants arrived at atmospheric design points by revisiting the permissible lower limit on the operating space for partial pressure of oxygen (mitigating hypoxia risk), and the permissible upper limit on fractional concentration of oxygen (mitigating flammability risk) via the utilization of materials qualified at higher oxygen fraction levels than currently used.

A significant topic of discussion was over the latter issue, since it was felt that setting an operating point above 30% oxygen would be possible, but might incur costs in time, money, and available materials & equipment that would be difficult to support in the near term. This was not resolved by the workshop for all missions, but a solution was proposed for the nearest term vehicle, the CEV, by determining that Shuttle standards for atmospheres and materials were appropriate for its role as a transport vehicle with only contingency EVA requirements.

EAWG process issues were also addressed by the reviewers. These included the utility of the Fault Tree Analysis (FTA) and Analytical Hierarchy Process (AHP) methodology in helping to make atmosphere design point selections. The response from most reviewers was that the FTA process was not an appropriate fit to the atmosphere selection issue, given the current uncertain state of knowledge of many of the risk factors. The AHP process had a mix of evaluations on its value in selecting points. Generally, the reviewers expressed that their time was not best spent evaluating the processes, but by applying their collective knowledge to discuss with the EAWG members the underlying risk issues and atmosphere design point selection. Other reviewers questioned the selected risk factors themselves, the weighting of these factors and the selection of atmosphere design points (e.g. no points selected by the EAWG resided in the trade space region below the hypoxic boundary). Overall, the reviewers suggested that AHP and FTA analyses were appropriate vehicles to begin conceptualizing the various risks and factors involved in determining a design point, however, they may have been introduced too early in the process. The AHP analysis was better received than the FTA and was advocated for use again by the EAWG as a post-workshop activity with respect to the new design points.

Finally, the reviewers discussed the best way to present the results of the design point recommendations to Constellation management. The majority suggested that specific points be proposed, inside a range or “band” of acceptable values with a discussion of the risks over that range, to present a rational trade space to program management. The importance of the EAWG reaching a consensus on its recommendations was emphasized in order that they may be presented with the strongest possible technical and engineering support.

2. Workshop Objectives

As NASA plans human exploration missions and develops new spacecraft, space suits, and habitats, it must specify environmental requirements for the human-occupied systems. One such requirement is the definition of the human habitation atmosphere - pressure and constituent gases. Human-occupied environments must provide a safe atmosphere. Total atmospheric pressure and constituent gas composition must be consistent with human physiology, the space environment, the spacecraft or habitat design, and with space exploration mission objectives. Given new mission requirements, it is necessary to assess the optimum design parameters for the human habitable atmospheres (spacecraft cabins, planetary surface habitats, airlocks, space suits, and pressurized rovers).

This workshop was formed to validate the EAWG's recommendations for human-occupied atmospheres and the additional research and technology development to enable NASA to specify exploration atmosphere requirements. Both NASA-affiliated and select external experts were invited to participate in the workshop with the goal of addressing the following objectives:

- Validate the EAWG plan, process and analysis methods, and results
- Bring additional ideas into the process - including constraints, potential technical solutions, impacts, process, etc.
- Identify areas where additional research is needed

These objectives were accomplished through the review of white papers, mission assumptions, and research and technology needs prepared by the EAWG. In addition, the participants reviewed the results of the EAWG's ranking of candidate atmosphere designs and a specific reference design point.

3. Workshop Development

3.1 Planning Team

The Exploration Atmospheres Workshop planning team was comprised of both NASA civil service and contractor staff. Complementary areas of expertise and capabilities were represented in the team's membership as indicated in the profiles below. Planning team members representing the EAWG included -

- Donald Henninger, Ph.D. - Chair, EAWG, Chief Scientist, Crew and Thermal Systems Division, NASA Johnson Space Center
- Paul Campbell - Deputy Chair, EAWG, Office of Bioastronautics Exploration Research & Technology, NASA Johnson Space Center.

The Technology Integration Agent (TIA) provided project management, technical, and administrative support for the workshop. TIA is a technology solutions provider charged to identify, assess, and recommend technologies ranging from low-TRL R&T projects to commercially available products based on specific capability requirements, application, and targeted timeframe for use. TIA supports the analysis of requirements and technology assessments for which it utilizes multiple mechanisms (workshops, focus groups, seminars) aimed at infusing internal and external (industry, academia, other government) technical expertise. The following TIA staff members supported the EAW activities as members of the planning team -

- Julianna Fishman is a project manager with Lockheed Martin Space Operations at the NASA ARC.
- Michael Krihak, Ph.D. is currently a technical advisor to NASA ARC and provides expertise in the areas of materials science, biotechnology, MEMS, optics and analytical sciences.
- Katy Souza is a planning operations representative with Lockheed Martin Space Operations at the NASA ARC.
- Fritz Stawitcke, Ph.D. is currently a technical advisor to NASA ARC and provides expertise in medical measurement and life support technologies.
- Dionna Suess is an administrative assistant with Unconventional Concepts Inc. at the NASA ARC.

In addition to the planning team, other individuals played important roles as plenary session speakers, breakout session technical leads and facilitators, recorders, note takers, and support staff who oversaw workshop operations. Workshop technical and support staff are listed below in Table 3.1-1. Participating members of the EAWG are listed in Table 3.1-2.

Table 3.1-1 Workshop Technical and Support Staff

Name	*Affiliation*	*Role*
Anderson, Molly	Code EC2, NASA JSC	AHP Analyst
Collins, Cynthia	Lockheed Martin Space Operations	Recorder/Note taker
Cook, Dan	Bastion Technologies	Carpool Coordinator
Davis, Jeffrey	Code SA, NASA JSC	Plenary Speaker
Deckert, George	SAIC	FTA Analyst
Duffield, Bruce	ESCG	AHP Analyst
Hoffpauir, Kellie	USRA, Division of Space Life Sciences	Workshop Operations
Hopmeier, Michael	Unconventional Concepts, Inc.	Facilitator
Kovo, Yael	Lockheed Martin Space Operations	Website Design & Development
Miller, Gina	Lockheed Martin Space Operations	Recorder
Miller, Suzanne	Bastion Technologies	Recorder/Note taker
Okimura, Takeshi	Lockheed Martin Space Operations	Website Design & Development
Pacetti, Gail	USRA, Division of Space Life Sciences	Workshop Operations
Schanafelt, Carol	Wyle Laboratories	Note Taker
Shaw, Kim	Bastion Technologies	Recorder
Snyder, Tim	Lockheed Martin Space Operations	Facilitator
Stephenson, Lisa	Wyle Laboratories	Recorder
Thigpen, Eric	SAIC	FTA Analyst
Thorton, Clint	Code NX22/GHG, NASA JSC	FTA Analyst
Watkins, Bobby	Code AG, NASA JSC	Plenary Speaker
Watts, James	ESCG	AHP Analyst
Wren, Kiley	Lockheed Martin Space Operations	Facilitator

Table 3.1-2 Participating EAWG Members

Name	*Affiliation*	*Role*
Barghouty, Nasser	Code XD41, NASA MSFC	Plenary Speaker/Technical Lead
Buderer, Melvin	Code SK, NASA JSC	Participant
Campbell, Paul	Lockheed Martin Space Operations	EAWG Deputy Chair/ Plenary Speaker
Chambliss, Joe	Code EC1, NASA JSC	Participant
Conkin, Johnny	NSBRI	Plenary Speaker/Technical Lead
Ewert, Michael	Code EC2, NASA JSC	Participant
Fitzpatrick, Daniel	Code SD37, NASA JSC	Participant
Galbreath, Gregory	Code ES2, NASA JSC	Participant
Gernhardt, Michael	Code CB, NASA JSC	Plenary Speaker/Technical Lead
Henninger, Donald	Code EC1, NASA JSC	EAWG Chair/ Plenary Speaker
Jones, Jeff	Code SD2, NASA JSC	Participant
Khan-Mayberry, Noreen	Code SF23, NASA JSC	Participant
Lange, Kevin	Jacobs Sverdrup Technology	Plenary Speaker
Lawson, Michael	Code EC1, NASA JSC	Participant
Lin, Chin	Code EC2, NASA JSC	Participant
Morin, Lee	Code CB, NASA JSC	Participant
Patrick, Jeff	Code XA, NASA JSC	Plenary Speaker/Technical Lead
Pedley, Michael	Code ES4, NASA JSC	Plenary Speaker/Technical Lead
Powell, Michael	Code SK, NASA JSC	Plenary Speaker/Technical Lead
Ruff, Gary	Code PTO0, NASA GRC	Plenary Speaker/Technical Lead
Trevino, Robert	Code EC5, NASA JSC	Plenary Speaker/Technical Lead
Urban, David	Code RUC0, NASA GRC	Participant
Waligora, Jim	USRA	Participant

3.2 Questionnaire and Pre-Work Material

Given the multidisciplinary nature of the EAWG's task to recommend optimal atmosphere design points, a considerable amount of technical resource material was prepared in advance of the workshop to support the efforts of the EAWG. To promote efficient use of the reviewers' time and expertise, a significant portion of the resource material that was presented and discussed at the workshop was provided as read-ahead material in advance. Select materials, including white papers and summary charts on particular session topics, were made available as downloadable files via the workshop website. Additional NASA references, such as the Bioastronautics Roadmap and references on the Vision for Space Exploration and NASA standards, were provided. The titles of read-ahead material provided to workshop participants are summarized in Table 3.2-1.

Table 3.2-1 Workshop Read-Ahead Material

Overview Section	***Title***
EAWG Process Review	EAWG Plan, Process, and Product
	Mission Systems Assumptions, Candidate Atmosphere Options, Trade Space
	Analytical Hierarchy Process - An Introduction
	Fault Tree Analysis - An Introduction
EAWG White Papers	Ambulation During Extravehicular Activity on Moon and Mars as a Risk Factor for Decompression Sickness
	Diluent Gas Options
	Dual Pressure EVA Suit
	The Effect of Long-Term Partial Pressure Oxygen Exposure
	Materials Flammability Control for Constellation Program: Impacts for Enriched Oxygen Environments
	Space Radiation Shielding Materials
Additional NASA References	Bioastronautics Roadmap
	Bounding the Spacecraft Atmosphere Design Space for Future Exploration Missions
	Human Systems Integration Standards
	NASA Flammability and Offgassing Standards
	The Vision for Space Exploration

A list of eight questions was developed to facilitate participant review and discussion of EAWG work to date. These questions were each addressed in specific workshop sessions to allow for focused reviewer input on particular issues. These questions are presented in Table 3.2-2.

Table 3.2-2 Workshop Questions and Associated Sessions

	Question Content	*Workshop Session*
Q1	Do the EAWG planned products directly support the exploration mission and systems architecture?	Plenary Session - Discussion of EAWG Results to Date
Q2	Is the EAWG process properly constructed to provide recommendations to ESMD?	Plenary Session - Discussion of EAWG Results to Date
Q3	What other risks are not identified by these white paper topics?	Breakout Session #1 – White Paper Review
Q4	What mission assumptions should be added or modified and how would these assist the EAWG in making its recommendations?	Breakout Session #1 – White Paper Review
Q5	How well has the EAWG's analysis process supported the conclusions to date?	Breakout Session #2 – Review & Consensus on Results
Q6	Do additional data exist in any of the areas that would support or change the conclusions of the EAWG?	Breakout Session #2 – Review & Consensus on Results
Q7	*What should EAWG's recommendations to Constellation Program be?	Plenary Session - Discussion on EAWG Recommendations
Q8	***How can EAWG most effectively proceed from this point?**	Plenary Session - Reviewer Discussion on EAWG Process

A brief worksheet consisting of the 8 questions was provided to participants who were requested to use the worksheet prior to the start of the workshop to capture their initial thoughts on the material provided so that over the course of the workshop their resulting input would be as complete and thorough as possible. In addition to questions, the worksheet also provided space for participants to suggest other resources (e.g. websites, publications, subject matter experts) that the EAWG may consider as it works toward making its final recommendations.

Questions 7 and 8 were modified prior to the start of the last plenary discussion by the EAWG chair. For reference, the original questions are listed below. The questions remained as stated below in the worksheet used by participants.

Q7: What are the most promising atmosphere designs?
- *Are there important candidate design points that EAWG did not consider?*
- *What are their pros and cons relative to each other?*

Q8: Has the process to rank/evaluate the candidate design points supported the conclusions?
- *Is EAWG membership scoring of the candidate designs adequate?*
- *Should the risk weighting be changed?*

3.3 Reviewer Selection

NASA subject matter experts and external subject matter experts with extensive expertise in technical areas tied to the space environment were selected as reviewers of the EAWG's work to date. Representatives of the Phase I prime contractors for the Crew Exploration Vehicle were also reviewers. The individuals selected had expertise in several medical, operational, and engineering disciplines and collectively were able to provide a substantive review of the range of EAWG working products. The following technical discipline areas were assembled:

- Active Thermal Control
- Combustion and Material Flammability
- Environmental Control and Life Support
- EVA Operations
- Physiology
- Safety
- Space Medicine
- Structural/Mechanical Design and Analysis
- Systems Engineering.

The names of the reviewers who attended the workshop are provided in Table 3.3-1 along with their area of expertise and affiliation.

Table 3.3-1 Workshop Reviewers

Name	*Expertise*	*Affiliation*
Bauer, Peter	Space Medicine	Code SD, NASA JSC
Bleisath, Scott	EVA operations	Code DX, NASA JSC
Bolton, Paul	Flight Controller. Operation of shuttle environmental control and active thermal control systems.	JSC Mission Operations Directorate
Chapline, Gail	Technical Assistant Director for Development	Code EA, NASA JSC
Davis, Jeff	Space Medicine	Code SA, NASA JSC
Fernandez-Pello, Carlos	Combustion, Material flammability	University of California - Berkeley
Hirsch, David	Flammability	Honeywell-WSTF
Jernigan, Mark	Life Support & Habitation	Code SA2, NASA JSC
Joshi, Jitendra	Life Support, Monitoring and Control and Systems	ESMD, NASA HQ
Kerwin, Joseph	Physiology and operations: Apollo, Skylab, Shuttle	Former Astronaut
Kennedy, Kriss	Habitation Systems Engineering	Code EC, NASA JSC
Lewis. John	Life Support Systems	Code EC, NASA JSC
Linteris, Gregory	Fire Safety; Microgravity Combustion	NIST
Maples, Whitney	ISS Life Support; ISS flight control	Code DF, NASA JSC
Marmolejo, Joey	EVA Systems	Code EC, NASA JSC
McCandless, Bruce	Former Astronaut	Lockheed Martin
Myers, Jerry	Computational Physiology, Biofluids	NASA GRC
Pilmanis, Andrew	Hypobaric/hyperbaric physiology and medicine; Altitude decompression sickness, hypoxia, pressure suits	Wyle Laboratories
Prisk, Kim	Pulmonary physiology	University of California – San Diego
Rotter, Henry	Life Support, Active Thermal Control & Analysis, and Fluids	JSC Engineering Directorate
Rouen, Mike	EVA Systems	Code EC, NASA JSC
Schmidt, Patricia		Boeing
Schultz, Denise	Space Station Safety Operations	JSC S&MA Directorate
Scull, Tim	Design and development of Environmental Control and Life Support (ECLS) hardware.	Hamilton-Sundstrand
Thurman, Randy	ECLS & TCS subsystems design for space vehicles.	Boeing
Webb, James T.	Decompression sickness (research, some NASA funded); Hypoxia (research, training)	USAF Retired
Zipay, John	Structural/Mechanical Design and Analysis, Systems Engineering	Code EX, NASA JSC

4. Workshop Results

4.1 Overview of Plenary Presentations

Overview presentations were made on the first day of the workshop to introduce participants to the approach and strategy utilized by the EAWG in developing supporting documentation and ensuing recommendations for human habitable atmospheres. EAWG members, NASA JSC management, and invited experts presented a range of topics to describe how the charter and work of the EAWG fit into the Exploration effort; the risk areas and multiple other considerations and factors associated with atmosphere design; assumptions made and the process and analytical tools used to build and support decisions; and how the EAWG's product will be used by the Constellation program.

The EAWG presented results of their analyses of nine potential atmosphere design points spanning the considered atmosphere trade space, plus a candidate reference design point referred to as "Point X". Point X is nominally 8.5 psia, 32% oxygen and meets NASA's hypoxia standards, while minimizing decompression sickness (DCS) risk and pre-breathe time to facilitate surface EVA's.

A structured plenary discussion followed this overview to capture participant comments related to this session and to answer questions clarifying the role of reviewers and the workshop objectives.

4.2 Plenary Discussion of EAWG Results to Date - Q1 & Q2

This session was structured to answer Q1 and Q2. The questions and a summary of discussion points are below.

Q1: Do the EAWG planned products directly support the exploration mission and systems architecture? Is the content appropriate? Will the delivery be timely?

Q2: Is the EAWG process properly constructed to provide recommendations to ESMD? Are the AHP and FTA appropriate tools for this analysis? How should the EAWG present results to ESMD to be most useful?

- Multiple comments that the goal is to define trade space and recommended design points within it to Constellation. Should describe cost, benefit, and risk functions inside the trade space and describe why going outside it is bad. Need to layout the trades considered to recommend future trades to Constellation beyond the one we're making now.
- Need to design now for a progression of vehicles and missions. Most urgent need is the early CEV design points. LSAM is secondary.
- Need to clearly document assumptions, such as no airlock on CEV, what contingency EVA means for CEV, etc.
- Capture development issues and operational issues separately.

- Need to make requirements clear.
- Need to present realistic costs (Schedule, Funding).
- Need to capture expertise of this group.

4.3 Breakout Session #1 -Review & Discussion of White Papers, Mission Assumptions, and Research Areas - Q3 & Q4

A review of the white paper topics is presented in this section. Each subsection includes three types of information: report-out charts, highlights of the report-out comments from the plenary session, and breakout session comments of note. Since the viewgraph summaries generated by each breakout group were the intended products of the focus group, the reproduced text of the report-out charts is provided first. The actual presentation of the report-out charts may be found in the appendix. Since the main points of the breakout groups are provided by the report-out charts, the highlights and breakout session summaries offer additional information that is not already presented by the report-out charts.

Also, each breakout group differed in size and in the expertise areas of the participants. As a result, each breakout group had its own working dynamics. Due to the variation in the way each group approached the questions, submissions to the data collection matrix in some instances were not entered in the tabular form that was anticipated by the templates prior to the workshop. Nonetheless, each of the groups responded with the appropriate set of report-out presentations that addressed the following questions -

Q3: What other risks are not identified by these white paper topics?
- What research, technologies, relevant experience, issues, etc. should be added for consideration?
- Are there risk mitigations or technologies available that may change the importance of some risks?

Q4: What mission assumptions should be added or modified and how would these assist the EAWG in making its recommendations?
- Does the ESAS Report require changes in our assumptions?

A list of each group's participants is below in Table 4.3-1.

Table 4.3-1 Breakout Session #1 Participant Lists

Group # 1 Flammability
Technical Lead: Michael Pedley
Facilitator: Tim Snyder
Recorder: Kim Shaw
EAWG Members: David Urban
Reviewers: Carlos Fernandez-Pello, David Hirsch, Gregory Linteris, Whitney Maples, Randy Thurman, Denise Schultze

Group 2 – Space Radiation
Technical Lead: Nasser Barghouty
Facilitator: Mike Hopmeier
Recorder: Lisa Stephenson
EAWG Members: Greg Galbreath, Chin Lin
Reviewers: Jitendra Joshi, John Zipay

Group 3 – Variable Pressure EVA Suit
Technical Lead: Robert Trevino
Facilitator: Mike Krihak
Recorder: Gina Miller
EAWG Members: Jeffrey Patrick, Molly Anderson
Reviewers: Peter Bauer, Scott Bleisath, Lee Morin, Andrew Pilmanis, Mike Rouen

Group 4 – EVA Ambulation
Technical Lead: Michael Powell
Facilitator: Kiley Wren
Recorder: Suzanne Miller
EAWG Members: Johnny Conkin, Mike Lawson, Mike Lawson, Mel Buderer
Reviewers: Joe Marmolejo, Jim Waligora, Patricia Schmidt

Group 5 – Atmosphere Gases
Technical Lead: Michael Gernhardt
Facilitator: Fritz Stawitcke
Recorder: Cynthia Collins
EAWG Members: Gary Ruff, Noreen Khan-Mayberry, Daniel Fitzpatrick, Jeff Jones
Reviewers: Paul Bolton, Bruce McCandless, Jerry Myers, Kim Prisk, James Webb, Tim Scull, Joe Chambliss

4.3.1 Flammability/Fire

Report-Out Charts

Tables 4.3.1-1 and 4.3.1-2 are summaries of the responses to questions #3 and #4, respectively, that were provided by the Flammability/Fire breakout group. Table 4.3.1-3 captures additional comments that were considered significant by the breakout group itself.

Table 4.3.1-1 Flammability Report-Out Chart for Question #3

Risk	*Additional Research Technologies, Relevant, Experience, Issues*	*Extramural Risk Mitigations or Technologies*
Water Based Fire Extinguishers	Issues with high-voltage power systems	-----
Crew Clothing	Off-the shelf, flammable outer clothing not suitable above 30% oxygen, custom clothing raises issues with wearability, clothing supplies, laundering, etc.	-----
Trash Spontaneous Ignition	Need to ensure that trash cannot self-heat to ignition in enriched oxygen	-----
Flammability of Dust on filters	Need to ensure flammable dust protected from ignition sources and cannot self-ignite	-----
Pyrolysis Products	Recommend controlling primarily through fire response (breathing masks, ECLS cleanup, etc.) rather than materials selection, but need to ensure fire response can address successfully	-----

Table 4.3.1-2 Flammability Report-Out Chart for Question #4

Assumption	*Assumption assistance in EAWG recommendations*	*Effect of ESAS Report*
Humidity Control/Static Electricity	Need to ensure minimum humidity controlled to eliminate static sparks as ignition sources, especially at high oxygen concentration (ISS 30-70% is fine)	-----
No air cooling of electronics	At high oxygen concentrations, lower total pressure reduces air cooling effectiveness. Also, coldplated sealed boxes provide much more effective flammability control.	-----
Use of COTS hardware	Current mindset on use of COTS will have to change for oxygen above 30%. Reduced crew friendliness	-----
Fire Detection technology	Need more small distributed sensors and better (different) sensor technology	-----

Table 4.3.1-3 Additional Comments – Flammability Report-Out

Other Considerations	*Open Issues*
Probably	None of these items considered closed

Report-Out Comments from Plenary Session – Summary

No comments were documented.

Breakout Session Notes/Matrix Summary

Q3: What other risks are not identified by these white paper topics?

This question focused on other risks not well addressed by the white paper topic. From the discussion, emphasis was placed on the higher oxygen concentration leading to a greater risk of flammability since the fire suppression capability will decrease. Concerns were also raised about the clothing and potential flammability hazard in greater oxygen concentrations. Another concern was the effect of dust build-up on HEPA (High Efficiency Particulate Air) filters and water vapor becoming a fire hazard in the presence of electronics.

The detection of a fire itself was also posed as a concern and that an increase in the number of detectors (small, distributed network ideally) and different detectors (from the ones currently used on the International Space Station (ISS) should be considered. Finally, the toxicity issues of pyrolysis products were also stated as being currently important.

Q4: What mission assumptions should be added or modified and how would these assist the EAWG in making its recommendations?

The goal of this question was to identify the mission assumptions that would assist the EAWG in making its recommendations. The plenary discussion identified the use of humidity/static control, a reduced pressure atmosphere (less air cooling), the use of COTS (commercial off-the-shelf) hardware, and a cabin atmosphere of greater oxygen content as issues.

4.3.2 Space Radiation Shielding

Report-Out Charts

Table 4.3.2-1 presents the results of the Space Radiation Shielding Materials report-out for question #3. The summary of assumptions is provided in Table 4.3.2-2 and additional noteworthy comments by the breakout group are presented in Table 4.3.2-3.

Table 4.3.2-1 Space Radiation Shielding Materials Report-Out Chart for Question #3

Risk	***Additional Research Technologies, Relevant, Experience, Issues***	***Extramural Risk Mitigations or Technologies***
1> Extended exposure chemical breakdown	Technology development, material maturation	Environmental shielding and isolation
2> In situ repair	Repair techniques, damage detection	Design for reparability; look at existing repair techniques (commercial or military)
3> Verification of shielding performance	Define environment, develop analytical tools, and in situ monitoring and testing	Look at existing verification strategies (micrometeorite, DSTB)
4> Knowledge of gaps and capabilities of multifunctional and mechanical properties	Extensive development and tests for primary structure applications	Improved design tools
5> Systems level compatibility and integration	Improved system modeling and integration	Improved design tools

Table 4.3.2-2 Space Radiation Shielding Materials for Question #4.

Assumption	*Assumption assistance in EAWG recommendations*	*Effect of ESAS Report*
1> Mission duration	Shielding requirements may depend on mission duration assumptions and affect atmosphere recommendations	-----
2> Limit and design of component lifetime	Optimal habitat design	-----
3> Exposure limits	Primary design driver for shielding requirements	-----
4> No secondary source of shielding for CEV and 7-day Lander	Atmosphere of CEV and Lander independent of shielding	-----
5> Assume that the only interaction between atmosphere and radiation shielding design is flammability	Material containment for flammability control with respect to point X	-----
6> Early requirements freeze	Enhances confidence in design activity post-SRR	-----

Table 4.3.2-3 Additional Comments – Space Radiation Shielding Report-Out

Other Considerations	*Open Issues*
Only natural radiation environment assumed; no man-made sources e.g. nuclear for surface power generation, are being considered.	-----

Report-Out Comments from Plenary Session – Summary

One comment provided during this session focused on the radiation shielding design for GCR (galactic cosmic rays) and SPE (solar particle event). It was noted that shielding against GCR will shield SPE, however, the shielding for the reverse is not true. During extended missions (longer than 6 months) on the Moon and/or Mars, most of the radiation dose is estimated to be from GCR exposure. Thus, SPE radiation exposure may not be as dangerous as GCR. Conversely, a short duration mission (< 1 month) such as a lunar excursion the astronaut would be mostly exposed to SPE. It was also noted that SPE may not be as dangerous as GCR.

Breakout Session Notes/Matrix Summary

Q3: What other risks are not identified by these white paper topics?

The responses to this question are well-captured in the Report-Out Charts. Additional comments were reported as follows:

<Risk 2> – *in-situ* repair

- Restoration to original structural capability

<Risk 3> – Verification of shielding performance

- What is the strategy to verify performance?

<Risk 4> – Knowledge of gaps and capabilities of multifunctional and mechanical properties

- Secondary structure applications are more realistic in the near term

Q4: What mission assumptions should be added or modified and how would these assist the EAWG in making its recommendations?

The mission assumptions requested by this question were reproduced in the Report-Out Charts. No other comments from the breakout session itself were recorded.

4.3.3 Variable Pressure EVA Suit

Report-Out Charts

The tables assembled by the Variable Pressure EVA Suit report-out group include Table 4.3.3-1, Table 4.3.3-2 and Table 4.3.3-3. These tables summarize the discussions of risks and assumptions for questions #3 and #4, respectively.

Table 4.3.3-1 Variable Pressure EVA Suit Report-Out Chart for Question #3

Risk	***Additional Research Technologies, Relevant, Experience, Issues***	***Extramural Risk Mitigations or Technologies***
Variable secondary regulator	Emergency system is "on our back"	-----
Operational regulation	Adds weight	Air Force using DCS computer for calculating risk
Assumption that if cabin is Point X, 0 pre-breathe would be required when donning a suit at 6 psig	Theoretical models must be validated by research	-----

Table 4.3.3-2 Variable Pressure EVA Suit Report-Out for Question #4

Assumption	*Assumption assistance in EAWG recommendations*	*Effect of ESAS Report*
Engineer out to low probability of Type II DCS	-----	-----
Habitat pressure will be higher than suit	Reduce weight	-----
Operational scenarios will keep EVA close to rover/habitat	-----	-----

Table 4.3.3-3 Additional Comments –- Variable Pressure EVA Suit Report-Out

Other Considerations	*Open Issues*
Having the lower secondary operating pressure is acceptable for failure of the primary system alone, but is not acceptable for DCS.	Automation of regulation would be the optimal system, however, this automation could affect the robustness and reliability of the suit.
Programmatic decision is required early on to possibly use the suit as a hyperbaric chamber. Any suit development would be impacted by a late decision (e.g., structural loads, variable pressure considerations)	-----

Report-Out Comments from Plenary Session – Summary

Suit design to accommodate pressures above 6 psig was identified as a possible measure for emergency hyperbaric treatment during an EVA. Concerns were expressed, however, that the suit integrity may be compromised if operating at those elevated pressures. It was suggested that a more rugged suit should be designed for future lunar or Mars missions to permit normal use after repeated hyperbaric treatments.

The attendees agreed on the need for more than two regulator set points. However, an upper limit of 3 or 4 set points was a distinct possibility with current regulators. If more set points are needed, then a new regulator design would need to be employed.

Breakout Session Notes/Matrix Summary

Q3: What other risks are not identified by these white paper topics?

Additional comments to the risks discussed during this session were in reference to a variable secondary regulator and operational rules. With regards to the former, the variable secondary regulator would need to be within 1-2 psig of the primary regulator. For the latter, the Air Force was identified as having a DCS computer for calculating risk, but it was noted that this computer would need to be modified for space exploration missions.

Q4: What mission assumptions should be added or modified and how would these assist the EAWG in making its recommendations?

One assumption that was addressed was regarding engineering a low probability of Type II DCS risk into the suit design. Even though a very low probability may be achieved, one reviewer expressed that the complete elimination of such a risk cannot be accomplished.

One other question was whether it will be acceptable to use an emergency oxygen supply pressure that increases the risk of DCS. This comment was in regards to the mission assumption that the operational scenarios will keep EVA close to a rover or habitat.

Other Notes

Discussion during this session also addressed three other topics related to a variable pressure EVA suit. The first topic was defining the variable pressures and that these pressures would actually be discrete points that are achieved within the suit. A second item was determining the lowest operating suit pressure. With the current regulators, a suit pressure of 3.5 psig could be achieved with confidence. When factoring other suit parameters such as glove dexterity, operating at 3.5 psig versus 4.3 psig would not provide much advantage. In conclusion, the EVA breakout group agreed that a 4.3 psig nominal suit operating pressure was most appropriate.

4.3.4 EVA Ambulation Effects

Report-Out Charts

This session reported its results with two tables, one each for questions #3 and #4. Table 4.3.4-1 lists five additional research suggestions and Table 4.3.4-2 identifies seven mission assumptions to guide ambulation risk assessments.

Table 4.3.4-1 Ambulation Effects Report-Out Chart for Question #3

Risk	*Additional Research Technologies, Relevant, Experience, Issues*	*Extramural Risk Mitigations or Technologies*
<Risk 1>	Look at historical data from Apollo training and surface ops for DCS	-----
<Risk 2>	Other non NASA data involving different types of exercise (e.g., World War II) for DCS	-----
<Risk 3>	Need to perform chamber tests with ambulation and determine which kinds of ambulation best simulate lunar surface activity (climbing, swinging arms, upper body)	-----
<Risk 4>	May need to test for pulmonary shunt and patent foramen ovale and consider with regard to bubble arterialization.	-----
<Risk 5>	Conduct tests on well hydrated subjects.	-----

Table 4.3.4-2 Ambulation Effects Report-Out for Question #4

Assumption	*Assumption assistance in EAWG recommendations*	*Effect of ESAS Report*
<Mission Assumption 1>	Consider different atmospheres for LSAM & CEV	-----
<Mission Assumption 2>	Consider use of pressurized rover	-----
< Mission Assumption 3>	Design point X seems reasonable.	-----
< Mission Assumption 4>	Ambulation significantly increases risk of DCS	-----
< Mission Assumption 5>	Surface activities must be considered (upper body movement)	-----
< Mission Assumption 6>	Variable pressure suit might be smart option	-----
< Mission Assumption 7>	Try to design out the risk of DCS as much as possible in the design of the pressurized environments	-----

Report-Out Comments from Plenary Session – Summary

It was noted that helium has advantages over nitrogen, since it is more soluble and has more rapid washout from body tissues. The mode of EVA ambulation in partial gravity was proposed as an R&T topic (e.g. – is lunar loping different from gaits used in ground testing?). NASA exploration EVA ground testing will begin in 2006 to study different ambulation types.

Breakout Session Notes/Matrix Summary

No additional comments from session.

4.3.5 Atmosphere Gas Constituents

Report-Out Charts

Table 4.3.5-1 represents the working group's suggestions, segmented by mission, for partial pressure of oxygen (pO_2), diluent gas options, and total cabin pressure. Table 4.3.5-2 contains additional data and suggestions to address both questions #3 and #4.

Table 4.3.5-1 Atmosphere Gas Constituents Group Results

	CEV	***CEV/LSAM***	***Outpost***
Hypoxia	Use existing Shuttle standards.	- Push back on limits to increase design space. - Want a nominal range of 5,000 to 8,000 feet, including sensor error.	- Push back on limits to increase design space. - Want a nominal range of 5,000 to 9,000 feet, including sensor error.
Diluent Gases	Use existing Shuttle standards.	<u>- Nitrogen Baseline</u> - Helium offers significant decompression advantages if required due flammability issues. Drawback - Significant engineering challenges.	<u>- Nitrogen Baseline</u> - Helium offers significant decompression advantages if required due flammability issues. Drawback - Significant engineering challenges.

Total Pressure	10psia to 14.9psia	- 8-8.4psia (nominal 8.2psia), with a range of O_2 concentration of 27.6% to 34%, nominal 30.7%	- 7.65-8.05psia (nominal 7.85psia), with a range of O_2 concentration of 27.3% to 34%, nominal 30.6%

Table 4.3.5-2 Additional Items Referencing Q3 and Q4

• Human testing to validate pre-breathing protocols.
• Variable pressure suit to expand capability, increase EVA performance, and safety.
• If forced to Helium option, it will require additional pre-breathe studies, engineering evaluations.
• Argon is an undesirable pre-breathe gas. If engineering trade studies suggest benefit, then additional pre-breathe.

Report-Out Comments from Plenary Session – Summary

The use of helium as a potential diluent gas raised engineering issues, such as speech intelligibility, and thermal control of electronics. The reply was that these are all solvable. There were comments that a mixed gas (including helium) outweighs the cost of testing and evaluation. It was stated that tolerance on nominal operating ranges were based on a maximum cumulative error of 0.2 psia from the sensor and the controller.

The issue of upper limit on carbon dioxide was not addressed in the session. One participant said it was a partial pressure of 5 mmHg (0.1 psia). It was also noted that slight hypercarbia enhances hypoxia tolerance, however other issues might arise. It was asked whether any issues might arise from having crew members acclimated to 9000 feet, then going to sea level oxygen partial pressure to perform an EVA.

It was asked whether there have been any studies on living for long periods at lower total pressures. The reply was that most effects of altitude that have been studied are due to reduced pO_2. However, lower total pressure means that food preparation and processing, as well as food growth, will be an issue (cooking at lower pressures, growing plants). The question was also raised of possible low pressure/low pO_2 effects on metabolism (e.g., food absorption and nutrition, changes in cognitive capabilities). It was next asked if the proposed atmospheres eliminated dedicated pre-breathe (meaning time beyond that required for suit checkout). The answer was yes, subject to studies. Citations of research on going to increased hypoxia will be provided by Jeff Jones. EAWG had previously assumed a limit of 6000 feet, it is now proposed to go to a higher altitude equivalent. Although the habitats will be hypoxic, it was noted that

EVA periods still will be conducted in slightly hyperoxic conditions, therefore hypoxia-induced performance reductions during EVA are not expected.

Breakout Session Notes/Matrix Summary

It was stated that a key role for lunar missions will be to validate surface operations approaches before Mars missions. They should be designed with equipment and protocols that allow study of chronic vs. acute hypoxia exposure effects, in reduced gravity and total pressure.

It was pointed out that there will be additional engineering challenges to utilizing helium such as a higher leak rate and more challenging storage conditions.

4.4 Breakout Session #2 – Review & Consensus on Results and R&T Recommendations – Q5 & Q6

The results of the review and consensus with regards to the three sets of discipline-area factors evaluated by the EAWG are presented in this section. These discipline-areas are (1) Physiological and Medical Factors, (2) Mission Operations Factors, and (3) Vehicle-Habitat System Factors. These main categories are covered in three parts: report-out charts, highlights of the report-out comments from the plenary session, and comments captured in the data collection matrix as well as notes logged by note takers that were assigned to each breakout group. The viewgraph summaries generated by each breakout group were the intended products of the focus group and thus, the reproduced text of the report-out charts is provided first. The actual report-out presentations may be found in the Appendix. Since the main points of the breakout groups are provided by the report-out charts, the two sub-sections that summarize the plenary session highlights and breakout notes comprise the main thoughts and comments by the meeting attendees not already captured in the report-out viewgraphs.

Also, each breakout group differed in size and in the expertise areas of the participants. As a result, each breakout group had its own working dynamics. Due to the variation in the way each group approached the presented questions, entries to the data collection matrix in some instances were not in tabular format as anticipated prior to the workshop. Similarly, remarks captured by the note takers were not assigned specifically to each question, but rather in a chronological account of the discussion that materialized. Overall, each of the groups responded with the appropriate set of report-out presentations that served to address the following questions:

Q5: How well has the EAWG's analysis process supported the conclusions to date?
- *What topics were not identified in the review process? How important are these identified topics (High, medium, low)?*
- *Are there any issues that are not adequately reflected in the findings?*

Q6: Do additional data exist in any of the areas that would support or change the conclusions of the EAWG?
- *What data need to be obtained before a further down-select of the candidate atmospheres is done?*

- *What R&T recommendations would you add? How important are these identified topics (High, medium, low)?*

A list of each group's participants is below in Table 4.4-1.

Table 4.4-1 Breakout Session #2 Participant Lists

Group 1 - Physiological & Medical
Technical Lead: Johnny Conkin
Facilitator: Fritz Stawitcke
Note Taker: Cynthia Collins
Recorder: Gina Miller
FTA Analyst: George Deckert
AHP Analyst: James Watts
EAWG Members: Daniel Fitzpatrick, Michael Gernhardt, Michael Powell, Jeff Jones
Reviewers: Peter Bauer, Bruce McCandless, Lee Morin, Jerry Myers, Andrew Pilmanis, Kim Prisk, Jim Waligora, James Webb

Group 2 - Mission Operations
Technical Lead: Jeff Patrick
Facilitator: Kiley Wren
Note Taker: Suzanne Miller
Recorder: Kim Shaw
FTA Analyst: Eric Thigpen
AHP Analyst: Molly Anderson
EAWG Members: Robert Trevino
Reviewers: Jitendra Joshi, Joey Marmolejo, Mike Rouen, Patricia Schmidt, Paul Bolton, Whitney Maples

Group 3 - Vehicle & Habitat
Technical Lead: Gary Ruff
Facilitator: Mike Krihak
Note Taker: Carol Schanafelt
Recorder: Lisa Stephenson
FTA Analyst: Clint Thorton
AHP Analyst: Bruce Duffield
EAWG Members: Chin Lin, Gregory Galbreath, Mike Lawson, Michael Pedley, David Urban, Noreen Khan-Mayberry, Nasser Barghouty
Reviewers: Carlos Fernandez-Pello, David Hirsch, John Lewis, Gregory Linteris, Henry Rotter, Tim Scull, Randy Thurman, John Zipay

4.4.1 Physiological and Medical Factors

Table 4.4.1-1 reports the group’s comments on the use of the FTA and AHP tools for risk analysis, in response to question #5.

Table 4.4.1-1 Physiological and Medical Factors Report-Out Chart for Question #5

AHP Analysis - about “process”
• A methodology that ranked atmosphere preferences based on your assessment of relative risks of the variables involved.
• Ops and physiology subgroups preferred lower pressure and higher oxygen concentration.
• Materials / Flammability subgroup preferred higher pressure and lower oxygen concentration.
• The main contribution of this method was to quickly and objectively eliminate what otherwise appeared to be reasonable atmosphere options.
• The external reviewers, in general, felt this method was an important component of the process that got us to Design Point X, and beyond.
• Several commented that it was not a good use of their time to evaluate “process”.

FTA Analysis - about “process”
• Hypoxia was not an issue since all atmosphere options were better than 6000 feet air-equivalent.
• P(DCS) was provided for each candidate atmosphere, so this unique feature of the FTA was not necessary.
• Therefore, the FTA in our particular application was not helpful – also not a lot of time to get this complex analysis done.

The next three tables address question #6. Table 4.4.1-2 describes the group’s review of the EAWG pre-workshop list of 17 suggested R&T topics for physiological and medical factors. Table 4.4.1-3 contains additional comments on some issues that will arise if new diluent gas alternatives are considered. Table 4.4.1-4 represents an updated list of R&T needs (additions and modifications in red italics).

Table 4.4.1-2 Physiological and Medical Factors Report-Out Chart for Question #6

• We reviewed 17 R&T areas, improved some of the wording, and added two new topics.
• Lots of discussion over 19 topics, most was captured in our notes.
• In general, the external reviewers agreed with the priority ranking (H,M,L) of the topics.
• Some felt that a few low priority topics could be removed from the list, but all will go forward since they serve as place holders for new research data.
• Specific data from Brooks AFB are available to address several topic areas, which would prevent unnecessary new research.

Table 4.4.1-3 Notable Comment Physiological and Medical Factors Report-Out

• The first-time use of helium or argon in a NASA vehicle may not be as far-fetched as it first sounds if materials selection, radiation shielding, and flammability are big challenges at higher oxygen concentrations.
• There are significant engineering and physiological research issues with long lead time if a trade study favors an inert gas in addition to nitrogen – tri-gas.
• The use of nitrogen, argon, and carbon dioxide on mars is likely a deciding factor to achieve a long-term presence on mars; maybe argon is just used on the return trip to earth.

Table 4.4.1-4 Physiological & Medical R&T Needs
Additions and Modifications made on 11/2/2005 at Workshop in italics

Topic	*Priority*
• Can an ISS-like pre-breathe protocol be used to extend the cabin atmosphere design space?	**Low**
• What is the probability of DCS as a function of tissue ratio under microgravity, Moon and Mars partial gravity?	**High**
• What is the most effective pre-EVA Decompression Sickness (DCS) prevention strategy to include pre-breathe with various gases, exercise and other medical measures?	**High**
• What are the appropriate screening procedures to minimize predispositions for DCS?	**Low**
• What are the resources and techniques for early diagnosis of DCS signs and symptoms, including the use of Doppler U/S and other bubble detection technologies?	**Low**
• What are the best methods for predicting DCS risk and for reducing the risk, based on understanding of the physiological mechanism for bubble formation and propagation, employing best available knowledge from flight and analog environment experience?	**Medium (one vote for High)**
• What are the most effective yet safe, and energy- and space-efficient means of managing DCS in the space flight milieu, including the use of hyperbaric oxygen delivery and other promising technology, and how might they be adapted for reduced-G operations?	**High**
• What is the risk of DCS after an acute environmental insult - e.g., leaking module or damaged EMU, and what treatment or response options are available under these off-nominal situations?	**High**
• What are the operational and medical impacts of off-nominal performance of DCS countermeasures?	**High**
• What are the risk factors that can increase the likelihood of DCS, such as the presence of Patent Foramen Ovale (PFO)?	**High**
• What is the likelihood of surviving an acute environmental insult severe enough to cause damage to the vehicle or spacesuit?	**Low**
• Is it possible and what are the DCS risk mitigation options for interplanetary EVA (e.g., moon and Mars) given that a tri-gas breathing mixture including argon is present?	**High**
• What is the role of individual susceptibility, age and gender on the risk of DCS during NASA operations involving decompression?	**Medium (one vote for High)**
• What are the available and new technologies needed to provide DCS treatment options on the ISS and future habitats (or vehicles) beyond LEO (e.g., on the moon or Mars)?	**Medium**
• What is the correlation between the detection/existence of gas phase creation in the bloodstream and development of clinically significant DCS?	**Low**
• What are the combined effects of long-duration mild hypoxia, hypobaria, and hypogravity on the human body?	***Low (new)***
• Oxygen Partial Pressure, Diluents, and Gravity: Other diluents (other than N_2) must be evaluated with respect to DCS, pre-breathe protocols, hypoxia risk, and other physiological effects.	***Low (new)***

11 / 02 / 05 additions	
• *What are best treatment strategies to manage ebulism?*	***High***
• *Understand more about the expected advantages of doing EVAs once equilibrated to a hypobaric environment.*	***Medium***

Report-Out Comments from Plenary Session – Summary

There was significant uncertainty and discussion on the risk posed by the flammability of hair, due to some conflict between space experience & other data. There were two new R&T issues proposed, one of which (ebulism treatment) does not affect atmosphere selection per se, but is a risk factor to refer forward to the Bioastronautics Roadmap.

Breakout Session Notes/Matrix Summary

The recorded session matrix includes numerous comments made during the discussion of each of the R&T needs entries, not reproduced here, but should prove useful for review by the Physiological & Medical subgroup of the EAWG.

4.4.2 Mission Operations Factors

Report-Out Charts

Tables 4.4.2-1 and 4.4.2-2 are the reproduced charts for Mission Operations Factors commentary on AHP and FTA analyses, respectively. Table 4.4.2-3 compiles the requested unidentified topics for both AHP and FTA. Finally, Table 4.4.2-4 provides the report-out chart for Question #6.

Table 4.4.2-1 Mission Operations Factors Report-Out Chart for Question #5, Part 1 - AHP

AHP Analysis - Analysis Process Support Conclusions
• Informative but preliminary. May help to downselect to other options.
• Perform another round of analysis and take into account ESAS results, cost, schedule, and risk.
• Reconsider relative to possible hypoxia limit change.
• Unclear how design point X resulted from AHP.
AHP Analysis - Issues Not Adequately Reflected
• ESAS results, cost, schedule, and risk and point X and Y (push hypoxia limit). Participants should provide input from program manager perspective rather than expert opinion.

Table 4.4.2-2 Mission Operations Factors Report-Out Chart for Question #5, Part 1 - FTA

FTA Analysis - Analysis Process Support Conclusions
• The complete FTA Models developed by other sub teams were not shared with entire team so it was an incomplete FTA Model.
• FTA Model that the Mission Op Sub Group developed only focused on mission success.
• FTA Model did not help with AHP assessment.

Table 4.4.2-3 Mission Operations Factors Report-Out Chart for Question #5, Part 2 for both AHP and FTA

Unidentified Topics	*Importance of Unidentified Topics (low, medium, high)*
ESAS results, cost, schedule, and risk and point X and Y (push hypoxia limit). Participants should provide input from program manager perspective rather than expert opinion.	-----

Table 4.4.2-4 Report-Out Chart for Question #6

EAWG Conclusion	*Existing Data to Support, Change Conclusions*	*Additional Data for Further Down-Select*	*Added R&T Recommendations*	*Importance of Identified Topics (High, Med., Low)*
-----	See AHP Round 3 comments above.	-----	More cross-education across sub-groups (either by team formation or briefings).	-----

Report-Out Comments from Plenary Session – Summary

Several issues were raised during the plenary session for Mission Operations Factors. Some of the emphasized concerns included cost, and flammability. Even though cost was not a factor emphasized by the EAWG, it was nonetheless assumed to be an important factor in the way management will select a cabin atmosphere. A comment was made that building a CEV to handle a 40% oxygen atmosphere was not cost prohibitive, rather the other contents (e.g. portable equipment) that would be added to the vehicle could provide much of the cost increase related to materials certification. In short, the materials will need to be qualified in an atmosphere greater than 30% oxygen. There was also speculation that the CEV would need to support variable atmospheres and pressures for the different types of planned future missions as well as different radiation shielding. The risks of DCS and fire were also addressed. The DCS risk was conveyed to be a moderate probability with moderate consequence, whereas fire was considered a low probability with high consequence. It was commented that fires were probably going to happen, so an approach to mitigate the effects should be a consideration.

For presenting the findings to management or Constellation, it was suggested that other options in terms of cost should be provided along with the recommended atmosphere. In addition, these suggested changes to the atmosphere should be provided sooner rather than later because once the CEV design is locked-in, it will be difficult to re-engineer to accommodate higher oxygen content atmospheres and other gas constituents. Along these lines the final recommendation was advised to be an operating point, but additionally provide a broader operating band for alternate decisions. Finally, a third AHP after the workshop was suggested to further support the validity of the findings.

Breakout Session Notes/Matrix Summary

Q5: How well has the EAWG's analysis process supported the conclusions to date?

This question focused on the evaluation of the AHP and FTA processes. In general, the results of the processes themselves were not well received and it was questioned whether or not outside reviewers should be responding to this question. A comment was captured stating that AHP is a better tool at this stage due to the lack of quantitative data. When the data exists, then FTA is the better tool. The consensus from the group was to wait on determining an analysis method. As a result, only a few comments were captured with respect to AHP and FTA.

AHP analysis was found to be informative but preliminary to help down select to other options. In addition, one reviewer suggested that a another round of analysis be performed that takes into account the ESAS results, cost, schedule, risk, and a possible hypoxia limit change. Finally, it was unclear to some reviewers how Point X resulted from the AHP process.

One reviewer questioned why hypoxia wasn't weighted more heavily in the AHP process. Another participant expressed that FTA may be more useful later in the program. Finally, the application of mathematical models was suggested to have the capability to derive probabilities of loss of crew event for DCS, but it was also noted that such models would need to be validated in the future.

Q6: Do additional data exist in any of the areas that would support or change the conclusions of the EAWG?

Notes for this breakout session were all captured under Question #5, none of which were specifically emphasized as responses for this question.

4.4.3 Vehicle-Habitat System Factors

Report-Out Charts

Table 4.4.3-1 presents the results of the Vehicle-Habitat System Factors report-out for Question #5 that pertain to AHP analysis.

Analytical Hierarchy Process

- Can be a useful tool but there was insufficient time for the review panel to understand process, weightings, and implications (uncertain pay-off)

Table 4.4.3-1 Vehicle-Habitat System Factors Report-Out Chart for Question #5

Does the Analysis Process Support Conclusions?
• Uncertainty in how the expertise of the EAWG influenced the results
• Uncertainty in how the weighting influenced the results
Issues Not Adequately Reflected
• There should be more than four categories; they don't address all the risks that a program manager would want to see (do these influence atmosphere selection)
• Specific impacts on systems should be included (life support, thermal, fire suppression, costs)
• No hypoxic design points were included in the original analysis (Points 1-9, X)

Table 4.4.3-2 presents the results of the Vehicle-Habitat System Factors report-out for Question #5 that pertains to Fault Tree Analysis.

Fault Tree Analysis

- Issues identified in the fault tree were relevant to assess flammability
- Analysis helps to focus thought on flammability risks for vehicle but ...

Table 4.4.3-2 Vehicle-Habitat System Factors Report-Out Chart for Question #5

Does the Analysis Process Support Conclusions?
• May not be best format to capture what is needed in this group
• Best applied after vehicle has been designed
• Can't assess probabilities at the high-level required without a design
Issues Not Adequately Reflected
• Death/Permanent injury due to fire is too general; there are many ways that a fire could injure a crew or impact a mission such as production of toxic products by fire or fire response, burns, equipment damage...
• Probabilistic Risk Assessment could be more useful to identify risks and focus attention on the highest risk issues during the design process

Q5: How well has the EAWG's analysis process supported the conclusions to date?

FTA and AHP helped to focus thought on the issues but the output of these results do not make a strong case for the selection of an atmosphere. Discussions of the EAWG and white papers have been more useful.

What topics were not identified in the review process? How important are these identified topics (High, medium, low)?

- Topics not identified include effects on thermal control, life support systems, fire suppression, costs, etc. These would be the real drivers and are the areas where a program manager would want to see trade studies.

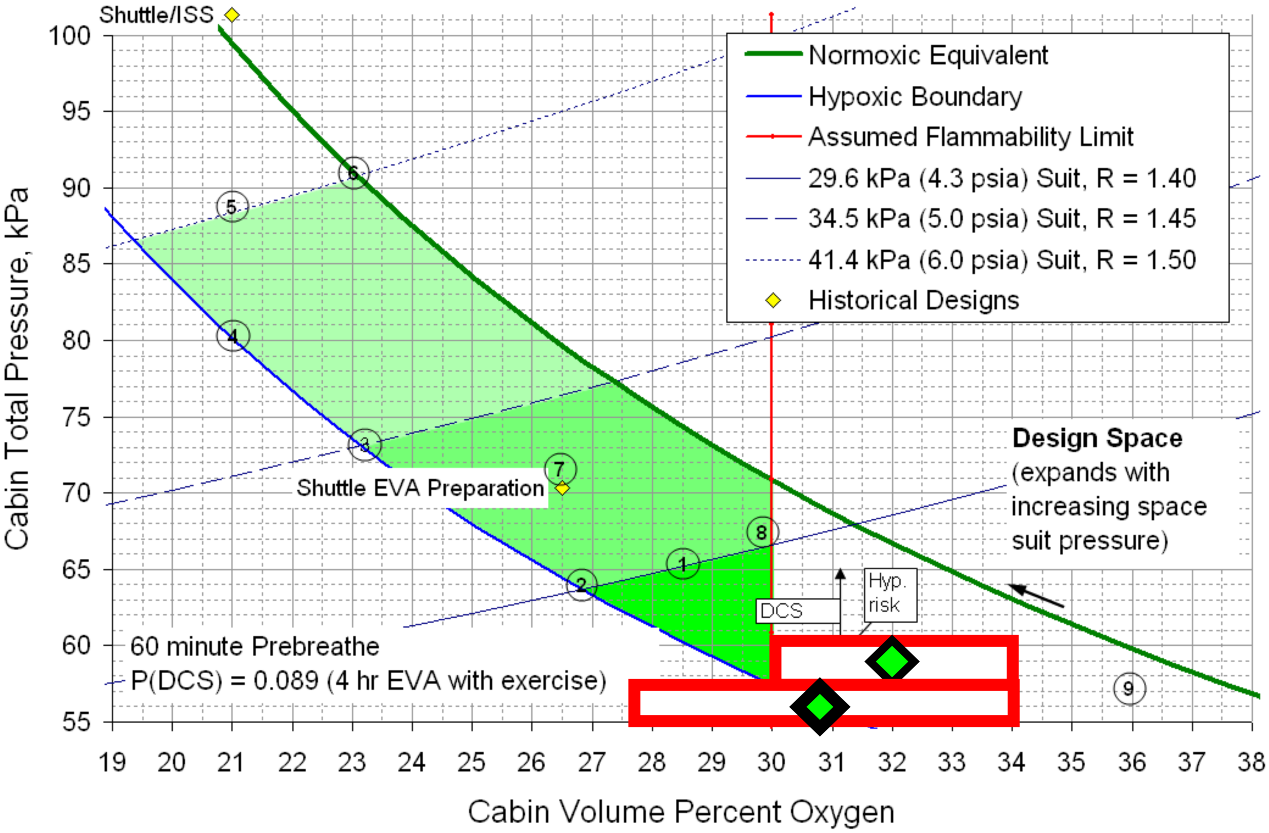
Are there any issues that are not adequately reflected in the findings?

- Yes

Figure 4.4.3-1 shows the proposed trade space, Point Y, proposed during the workshop with respect to the other nine design points considered by the EAWG and Point X, which was the final design point recommended at the start of the meeting. The actual atmospheric design ranges are:

Point X: 8.5 psia, 32% oxygen;
Point Y: 8 – 8.4 psia, 27.6 - 34% O_2; 7.65 – 8.05 psia, 27.3 – 34% O_2.

Figure 4.4.3-1 EAWG Design Reference Points



In Figure 4.4.3-2 below, two design points (Point X and Point Y, where Point Y is the larger rectangle) were provided by the Vehicle-Habitat System Factors breakout group for proposed cabin atmosphere pressure and oxygen concentration.

Figure 4.4.3-2 Historical and Workshop Candidate Design Points

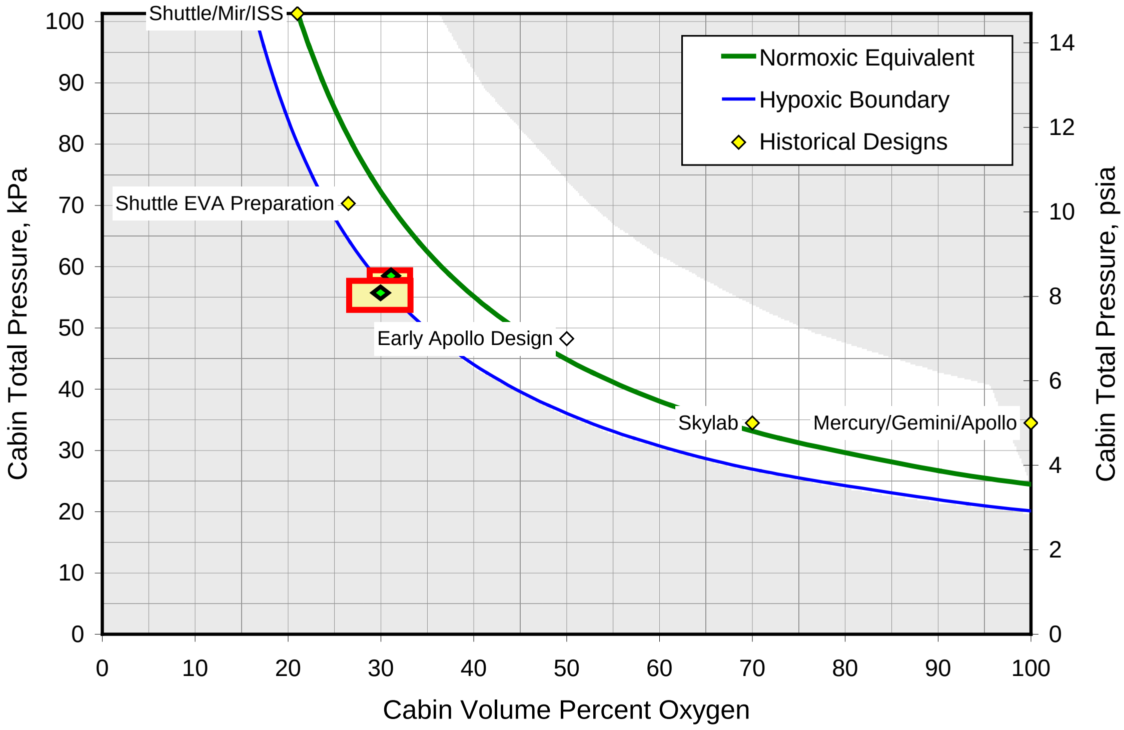


Table 4.4.3-3 provides a list of R&T needs generated by the Vehicle-Habitat Systems Factors group. Each topic was given an assigned priority level of low, medium, or high.

Table 4.4.3-3 Vehicle-Habitat System Factors R&T Needs

Topic	***Priority***
• Flammability effects of pressure, gravity, oxygen mole fraction, diluent gas	**High**
• Acceptable materials for clothing, windows, stowage foam, and radiation protection for O_2% above 30%	**High**
• Ignition mechanisms for high oxygen concentration systems (flow friction and particle impact)	**Medium**
• Detection of fires in alternate environments and atmospheres must be evaluated	**High**
• Development of fire suppression systems that are effective for oxygen concentrations > 30%; “No good story for putting out fires”	**High**
• Effect of atmospheric noise and voice communications	**Medium**
• Effect of low atmosphere pressure on food preparation and processing	**Medium**
• Methodology for maintaining configurations controls over long duration	**High**
• Impact on fire risk for step increase in %O_2, change in P; quantitative increase in risk between atmosphere with 30% and 36% O_2; What is the threshold on flammability?	**High**
• Quantitative impact of high O_2 on flammability, production of toxic products (gaseous and particulate), heat release	**High**
• Development and quantification of effectiveness of non-flammable coverings and coatings on flammable materials	**High**
• Methodology to assess total risk of fire to vehicle/habitat system	**High**
• Food Processing: Development of a EMI acceptable microwave oven	**High**
• Threshold for flammability of hair and skin	**Medium**
• Material flammability during medical ops	**-----**
• Burn treatment (external and inhalation) in reduced gravity	**-----**

Discussion and Comments

Table 4.4.3-4 summarizes the discussion that related to the feasibility of a 30% O_2 cabin atmosphere.

Table 4.4.3-4 Feasibility of 30% O_2 Atmosphere

In the white papers and break-out sessions, we have said that increasing %O_2 above 30% is feasible

- Design points have been developed that include higher %O_2 because we have done it before
  - Must have an answer for why not just go to 100% O_2 and 5 psia
- Apollo vehicles were tested extensively before flight (before they truly assumed the risk of 100% O_2)
  - Apollo was designed in an era of plenty of funding. Today, costs are a strong consideration.
  - Risk has always been a driver but risk is mitigated through pre-flight testing
    - "Smart" risks are acceptable but it is testing that makes the difference
- "No vehicle system since Apollo has undergone the same level of pre-flight testing."

Discussion and Comments (continued)

You can't accept "34% oxygen" without also immediately accepting the cost and schedule of the associated testing and development.

- Impact on thermal systems, life support equipment (new technologies), fire suppression, ... is unknown at this time

Additional concerns regarding a 30% O_2 cabin atmosphere are presented in Table 4.4.3-5.

Table 4.4.3-5 Other Issues

Costs are immediate

- There is a step change in costs to go above 30% O_2 (max)
  - Contractors will have to add costs of re-testing materials and systems at these conditions
  - This will be a consideration at PDR
- Uncertainty in how many materials will have to be tested but ...
  - Configuration and component operating tests will be extensive
  - Engineering issues can be addressed but development and testing is a critical
- Not accepting this cost and schedule impact is the same as setting the upper limit to 30% O_2

Discussion and Comments (continued)

How do we get out of this box?

Table 4.4.3-6 summarizes possible answers to the question posed here.

Table 4.4.3-6 Considerations for Succeeding with a ≥30% Atmosphere

Understand the margin of safety associated with a specific change in atmospheric condition, design, etc.
• Current tests are pass/fail at a specific condition
o Don't quantify a degree of failure to help assess incremental risk
• Propose a change in methodology to evaluate flammability of materials
o Toxicity of fire and pre-fire products (gaseous and particulates)
• Apply performance-based fire protection methodologies to fire protection on spacecraft
o Obtain data from material flammability testing at desired conditions
• Heat release, toxic products, flame spread rates, ignition sources ...
o Analyze impact on vehicle through entire fire scenario
• Detect and respond before system impact exceeds design envelope
o Requires testing (sub- and full-scale) and system simulation

Q6: Do additional data exist in this subgroup area that would support or change the conclusions of the EAWG?

Probably not

- What data need to be obtained before a further down-select of the candidate atmospheres is made?
  - Development and certification costs associated with going above 30% oxygen
  - Ability to accurately assess hypo-gravity material flammability
- Selection of materials and configurations
  - Non-flammable covering and coatings
  - Methodology for configuration control over the duration of a 2 – 3 year mission

Report-Out Comments from Plenary Session – Summary

The Vehicle-Habitat System Factors report-out raised several topics of conversation. One general comment was to justify a selection of 34% oxygen, above the 30% at which most materials are qualified for flammability issues, instead of just using 100% oxygen like was used in some past space missions, such as Apollo. The 30% barrier is important for newer classes of materials, however, that weren't available on missions over 20 years ago. Another participant commented on cost from the point of view that questioned the cost of items that one can't take with them when going to an atmosphere with over 30% oxygen. It was also noted that a comparison of the trade-off between DCS risk and pre-breathe efficiency costs should be taken into account. According to one participant, the cost at 30% oxygen content may be a significantly extended pre-breathe compared to 34% oxygen content. Since testing of materials has only been performed up to 30% oxygen, this oxygen concentration tends to be the abrupt cut-off value for flight qualified materials. It was noted that most of the expected increase in cost is in the new and different design approaches for the elevated oxygen content.

During this breakout report presentation, a new range of pressures and oxygen concentrations was presented and dubbed ‘Point Y.’ Since Point Y covered a range of oxygen concentrations from approximately 26% to 34% oxygen, one reviewer proposed a compromise to move to the left side of the box where values were below 30% oxygen content. Also, if such a design band is recommended then the vehicle will need to have variable pressure and atmosphere capability.

In addition to the previously discussed topics, radiation shielding was recommended to be adequate for all types of missions. Also, life support issues were raised that may not have been investigated yet

An overall recommendation was to obtain more information on the goals of the Constellation program and try to align the EAWG recommendation with them.

Breakout Session Notes/Matrix Summary

Q5: How well has the EAWG’s analysis process supported the conclusions to date?

During the breakout session, AHP and FTA were found not to be beneficial to the recommendation according to the reviewers. For AHP analysis, having only 4 factors was questioned and that the analysis may be performed at too high a level. Concern was also expressed for flammability, which may have different costs associated with those risks. Also, the selection of the ten points for evaluation was identified as not having a point that lies in the hypoxic range. To better verify the analysis, it may have been beneficial to have one or two evaluation atmospheres that lie below the hypoxic boundary.

Other items brought forward included the ability for engineers to design systems for a pre-determined atmosphere, if it is given to them in advance. Second, certain risks and system reliability may be greatly improved through comprehensive preflight subsystem and system-level testing, which may not be a feasible approach for the initial CEV (due to expected time constraints and funding issues).

The FTA model was suggested to possibly not be the best format to capture what the EAWG is seeking. Other factors were proposed to be built into the model that included toxic products produced by fire, an assessment of 30% oxygen atmosphere and the proper use of materials.

Q6: Do additional data exist in this subgroup area that would support or change the conclusions of the EAWG?

For assessing the EAWG recommendation, one reviewer was interested in determining what is the true impact of a 2% oxygen content increase in the vehicle (from 30% to 32%). The discussion also focused on flammability issues and ways to mitigate fire hazards such as painting items with an aluminum coating and to quantify the fire margin. It was also noted that personal items brought by astronauts such as toothbrushes and other paraphernalia need to be flight qualified, too. Furthermore, a request was made for NASA to consider a new standard methodology for fire testing that will yield oxygen concentration sensitivity data for each material.

Although not represented by an expert in the breakout session, food preparation issues were also highlighted by the group as a possible consideration for the CEV.

4.5 Reviewer Discussion on EAWG Recommendations – Q7 & Q8

Q7: What should EAWG's recommendations to Constellation Program be?

Several reviewers felt that multiple sets of atmosphere recommendations should be made, in the manner of the matrix created by the Atmospheric Gases breakout group, to serve the differing needs of multiple missions and vehicles - CEV, LSAM, and habitat. The majority suggested that specific points be proposed, inside a range or "band" of acceptable values. They further suggested providing a discussion of the risks over the range, in order to provide a trade space for program management to use.

Another recommendation was to select atmospheres for the landers and habitats in order to facilitate frequent and efficient EVA's, in particular by reducing the pre-breathe time. This led to suggested operating points that pushed the limits of acceptable hypoxia from the 5000 to the 9000-foot range, and lower total pressures. There was also a call to consider being less conservative about DCS risk, with the caveat that any new protocols needed to be studied in altitude chamber tests. It was noted that operation at oxygen levels equivalent to altitudes above 5000 feet will require a NASA hypoxia standard change.

Considerable debate took place over desirability vs. feasibility of operating with an oxygen concentration above 30%. The 'con' argument was that most modern materials typically used in the Space Shuttle and ISS are only qualified to pass flammability standards at that level, and the process of doing new qualifications would be costly and time-consuming, reduce the availability of COTS solutions, and increase the difficulty of specifying the CEV which is on a short timetable. The 'pro' arguments included a reduced EVA pre-breathe time, the present existence of technical solutions, and the assertion that it would be far more expensive and time-consuming to raise the oxygen limit later in the program. Several participants proposed that any new flammability testing be done over a range of oxygen concentrations, to provide trade space information.

It was stated that the CEV would not be used for routine EVA's, so its atmosphere design could be compatible with existing ISS and Shuttle standards. The more challenging proposals for oxygen concentration and partial pressure were for the transit vehicles and habitats, which have more lead time available to set specifications, engineer solutions, and perform experimental validation of protocols. It was suggested that ground-based testing of proposed atmospheres and pre-breathe protocols begin as soon as possible, to validate existing models of performance and DCS risk levels.

Several reviewers supported some form of multi-pressure regulator for space suits, though cautions of added complexity & weight were made.

Q8: How can EAWG most effectively proceed from this point?

Several reviewers emphasized the importance of reaching a consensus of the EAWG on specific recommendations, in order to give them sufficient weight to influence Constellation management. Some thought that the AHP method should be redone on the new suggested operating points. However, a larger number felt that a more effective process was to continue the open and vigorous technical dialogue among experts, until a well-considered compromise position was reached that everyone could support. In general, they did not feel that their time was well spent critiquing the FTA and AHP methods at this workshop.

5. EAWG Draft Consensus

The EAWG membership met during the last afternoon of the workshop to discuss the how the group would use the comments and suggestion made by the reviewers. The discussion was focused on arriving at a design point consensus recommendation segmented by vehicle. Table 5-1 summarizes the EAWG's draft consensus.

Table 5-1 Summary of EAWG Draft Consensus

	Operating Pressure Capability (psia)	*pO_2 Floor Capability/Permitted (mmHg)*	*O_2 Max (%)*
CEV / ISS (Block Ia)	10.2 – 14.7 (0-14.7)	115-128	30%
CEV / LSAM (Block II)	8.0 – 14.7 (0-14.7)	115-120	30% @ 8.5 psia 34% @ 8 psia
CEV / Outpost (Block III) Moon / Mars	7.6 – 14.7	115-115	34%
MT Habitat	10.2 – 14.7	130	30%
Surface Suit	3.5 – 4.3 (nom.) 8.4 (emergency)		

Issues associated with these design points include:

- Validation and change of a human standard for hypoxia (literature review)
- Cost and time required for DCS studies will be high, but necessary for these proposals
- Acclimation during various mission durations
- Air cooling at lower pressures (electronics)
- Material flammability issues across the 30–34% range
- Multiple food preparation applications
- Leak rates and total air leakage mass over extended mission times.

6. Appendices

The following documents may be found in the Exploration Atmospheres Workshop Report Appendix, a companion document to this report.

- Workshop Agenda
- Workshop Participants
- Plenary Session Presentations
- Tuesday, November 1
  - EAWG Process Overviews
  - White Paper Overviews
- Wednesday, November 2
  - EAWG Results Overview
  - Breakout Session #1 Charter and Reports
  - Breakout Session #2 Charter
- Thursday, November 3
  - Breakout Session #2 Reports
  - Reviewer Discussion on Recommendations
- Prework Instructions and Worksheet
- Completed Worksheets

7. Acronym and Abbreviation List

AFB – Air Force Base
AHP – Analytical Hierarchy Process
ARC – Ames Research Center
CEV – Crew Exploration Vehicle
COTS – Commercial Off-the-Shelf
DCS – Decompression Sickness
Doppler U/S – Doppler Ultrasound
DSTB – Deep Space Test Bed
EAWG – Exploration Atmospheres Working Group
ECLS - Environmental Control and Life Support
ECLSS – Environmental Control and Life Support System
EMI – Electromagnetic Interference
ESAS – Exploration Systems Architecture Study
ESCG – Engineering and Science Contract Group
ESMD – Exploration Systems Mission Directorate
EVA – Extra Vehicular Activity
FTA – Fault Tree Analysis
G – Gravity
GCR – Galactic Cosmic Ray
GRC – Glenn Research Center
HEPA – High Efficiency Particulate Air (filter)
HQ – Headquarters
ISS – International Space Station
JSC – Johnson Space Center
LEO – Low Earth Orbit
LSAM – Lunar Surface Access Module
MEMS – Micro Electromechanical Systems
mmHg – millimeters Mercury
MSFC – Marshall Space Flight Center
MT – Mars Transit
N_2 - Nitrogen
NASA – National Aeronautics and Space Administration
NIST – National Institute of Standards and Technology
O_2 – oxygen
P – Pressure
P(DCS) - Probability of Decompression Sickness
PDR – Preliminary Design Review
PFO - Patent Foramen Ovale
pO_2 – Oxygen Partial Pressure
psia – absolute pounds per square inch (ambient pressure)
psig – gauge pounds per square inch (suit pressure)
R&D – Research and Development

R&T – Research and Technology
S&MA – Safety and Mission Assurance
SAIC – Science Applications International Corporation
SPE – Solar Particulate Event
SRR – System Requirements Review
TCS – Thermal Control Systems
TIA – Technology Integration Agent
TRL – Technology Readiness Level
USAF – United States Air Force
USRA – Universities Space Research Association
WSTF – White Sands Test Facility

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13. ABSTRACT *(Maximum 200 words)*

The authors of this document recommend that, to enable missions to the moon and Mars, NASA's Constellation vehicles, habitats, and spacesuits employ an integrated set of internal atmospheres rather than a single design for all elements. These atmospheres must mitigate the risks of fire, decompression sickness, and hypoxia while enabling crew excursions on planetary surfaces. It should be noted that the recommendations provided in this document are not requirements; instead, they reflect technical considerations only. To support the recommendations made herein, Constellation should institute a modified standard NASA flammability test as soon as possible to generate ignition threshold data for key spacecraft materials. This modified test will allow the agency to identify materials at risk from increases in oxygen concentration, minimize potential impacts, and allow for development of sound requirements for landers and habitats. The Human Research, Technology Development, and Constellation Programs should also initiate activities to enable atmosphere designs for, respectively, human research, technology development, and program-specific studies to validate these recommendations for the Constellation habitable elements.

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