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Recommendations for Exploration Spacecraft Internal Atmospheres

The Final Report of the NASA Exploration Atmospheres Working Group

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Preface

This report is the 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 Earth's 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.

Executive Summary

To enable missions to the moon and Mars, it is recommended that NASA's Constellation vehicles, habitats, and space suits 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, 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 psia and 10.2 psia nominal total pressures. For lunar sortie missions, the docked CEV and lander (also known as Lunar Surface Access Module or LSAM), should operate at a nominal 10.2 psia total pressure, 26.5% oxygen concentration. These atmospheres ensure compatibility with ISS, do not preclude contingency EVA, and do not add significant cost or schedule burden to 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 feet. All recommended nominal atmospheres are assumed to be at the center of a control box of +/-0.2 psia total pressure and +/-2.0 percentage points oxygen concentration. The lower end of the lander atmosphere control box may extend to equivalent altitudes over 6000 feet, outside the current NASA standard for hypoxic conditions.

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

In-space and surface EVA suits should operate at a nominal 4.3 psia, 100% oxygen, consistent with current Shuttle/ISS suits. The surface suit should also have the capabilities to operate at the lander pressure (8.0 psia) for treatment of decompression sickness, at approximately 6.0 psia for rapid EVA egress, and at 3.5 psia in certain contingencies. All these atmospheres are within current NASA physiological standards for the 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 feet 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. The 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 Program, Technology Development Program, and Constellation Program 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.

1.0 EAWG 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 and the outcome of the 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 space suits 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's Earth sea level pressure and oxygen content.

The Vision for Space Exploration (NASA, 2004) specifies that NASA is to develop and execute human missions to Earth's moon, to Mars, and beyond. It emphasizes a long-term approach to NASA's human exploration of the Solar System. Interplanetary human spacecraft, planetary landers, space suits, pressurized rovers, and surface habitats may be developed to accomplish this goal. Each of these new vehicles will contain a habitable atmosphere to support the 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 and 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 NASA's design standards (Lange et al., 2005).

In 2005, the EAWG operated specifically within the framework of the Vision for Space Exploration (VSE) to refine the atmosphere trade space into a set of recommendations for exploration programs. This final report of the EAWG's 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 space suits and planetary exploration vehicles. Appendix A provides a complete list of the EAWG members.

The EAWG Implementation Plan, Appendix B, was generated in response to the ESMD request. It laid out EAWG objectives and a general plan for the EAWG membership, activities, and products. The overall EAWG objective was described as "refine the atmospheric design space to a relatively small domain such that atmospheric requirements for space-based systems can be specified." Table 1.2-1 lists the discipline areas represented by the EAWG membership.

Table 1.2-1 Disciplines Represented in Exploration Atmospheres Working Group

Physiological and Medical
Environmental physiology
EVA physiology
Space medicine
Toxicology
Mission Operations
Extravehicular activity operations
Extravehicular activity 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 the group's activities and analytical efforts. These included:

- Employ risk-based systems engineering analysis to achieve balanced risk mitigation.
- Utilize a long-range view that considers multiple interacting mission systems.
- Apply past NASA program experiences to make use of lessons learned and to leverage flight-proven technologies and techniques.
- Take advantage of insights and novel solutions available outside NASA.
- Strive for multi-discipline 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.

2.0 EAWG Process Overview

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

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

Additional analytical activities were conducted during September and October of 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's general meetings.

2.2 Overview of EAWG Analysis

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 EAWG's 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, in order to assess the degree of consensus among the members.

White papers were generated by EAWG members and associated NASA personnel to provide explanation 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.

3.0 EAWG Analytical Foundation

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

3.1 History of Spacecraft Atmospheres

Lange et al., (2005) provided a summary of previous NASA spacecraft atmosphere designs and operations, shown in Table 3.1-1.

Table 3.1-1 Historical Spacecraft Atmospheres
(From Lange et al., 2005)

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), the Apollo spacecraft atmosphere's on-orbit transition 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 3.1-1, 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.

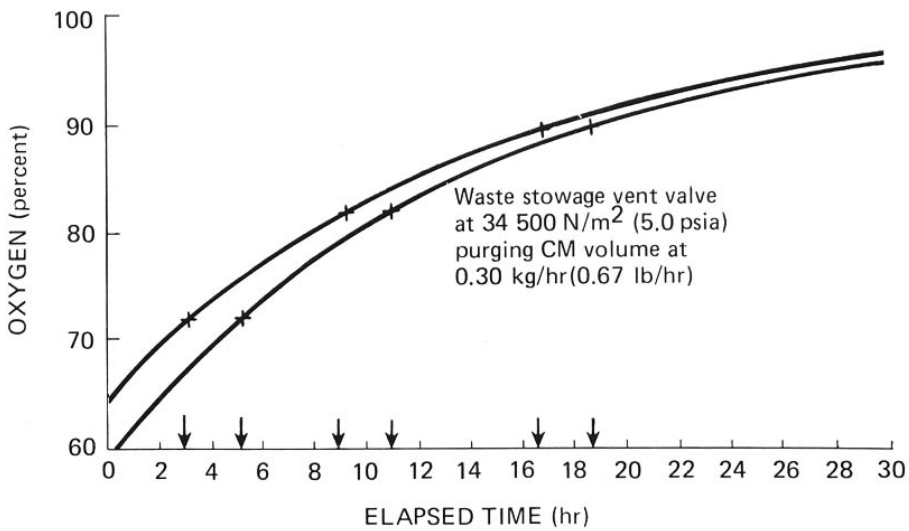


Figure 3.1-1 Apollo Command Module Atmosphere On Orbit Transition
(from Biomedical Results of Apollo, 1975)

3.2 Related Work

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

The NASA Bioastronautics Roadmap (NASA, 2005a) was a major source of research and technology issues and 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, 2005b) was conducted in parallel with the EAWG's work. The ESAS data released during 2005 were used by the EAWG as reference mission-systems information and are consistent with the recommendations in this report. However, the full ESAS report was not available to the entire EAWG during its analytical work.

The Exploration Extravehicular Activity (EVA) Suit Architecture Study was conducted in parallel with the EAWG's 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, however, 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, 2005c) 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 the EAWG's analyses and recommendations. NASA STD-3000, Volume I, Revision B, Human Systems Integration Standards (NASA, 1995) is invoked by the Human-Rating Requirements for Space Systems. NASA STD-3000 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's work, Agency-level human health standards were in preparation but were unpublished. JSC 26882, Space Flight Health Requirements Document (NASA, 1996) is invoked by the Human-Rating Requirements for Space Systems and 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 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 different from those stated in JSC 26882, these new standards could affect the EAWG's recommendations in this report.

NASA STD-6001, Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion (NASA, 1998) was also used as a source of information for the EAWG.

The JSC Design and Procedural Standards (NASA, 2005d), is also invoked by the Human-Rating Requirements for Space Systems. 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's process of deliberation and recommendation.

4.0 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

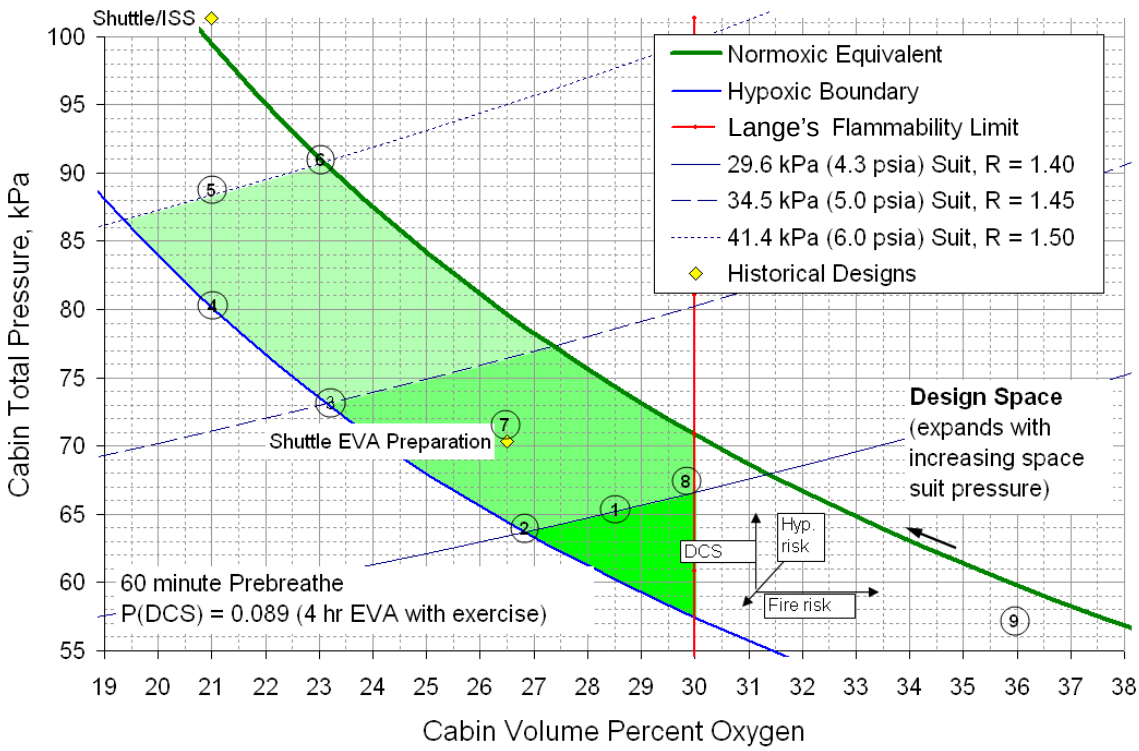
The EAWG began its deliberations using the six candidate atmosphere design points provided by Lange et al. The EAWG then added three more candidate design points, resulting in the set shown in Table 4.1-1 and Figure 4.1-1.

Table 4.1-1 EAWG's 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's estimate of the probability of decompression sickness. The P(DCS) was computed for each design point given a 60 minute in-suit prebreathe with an ambulatory subject performing a 4 hour 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: Normoxic Equivalent and Hypoxic Boundary taken from NASA STD-3000.
Lange's Flammability limit taken from Lange et al. (2005).
Oxygen concentrations in the figure are nominal and the upper control limits will be higher.

Figure 4.1-1 EAWG's Candidate Atmosphere Design Space

4.2 Study process

A risk-based analytical process was performed by the EAWG, examining in detail the following risks as they relate to the design of spacecraft atmospheres. These risks were used as the key Figures of Merit (FOM) for evaluation of the candidate atmospheres.

- Hypoxia: human performance degradation due to insufficient oxygen partial pressure available in the human lung.
- Decompression Sickness: injury/illness due to 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, Fault Tree Analysis (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. These 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 data

sets required to perform numerical calculations of the risk magnitudes with these FTA models were not available to the EAWG. Therefore the FTA analysis was concluded without calculating specific risk levels, but 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 Report was not available to the EAWG during the EAWG's 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 Report. When partial ESAS results became available late in the EAWG analysis cycle, they were reviewed and compared to the EAWG's common assumptions and small differences were identified that did not cause a significant change in the EAWG's approach or results. Figure 4.2-1 illustrates the EAWG mission-systems assumptions, as modified to match ESAS results that were available to the EAWG as of November 2005.

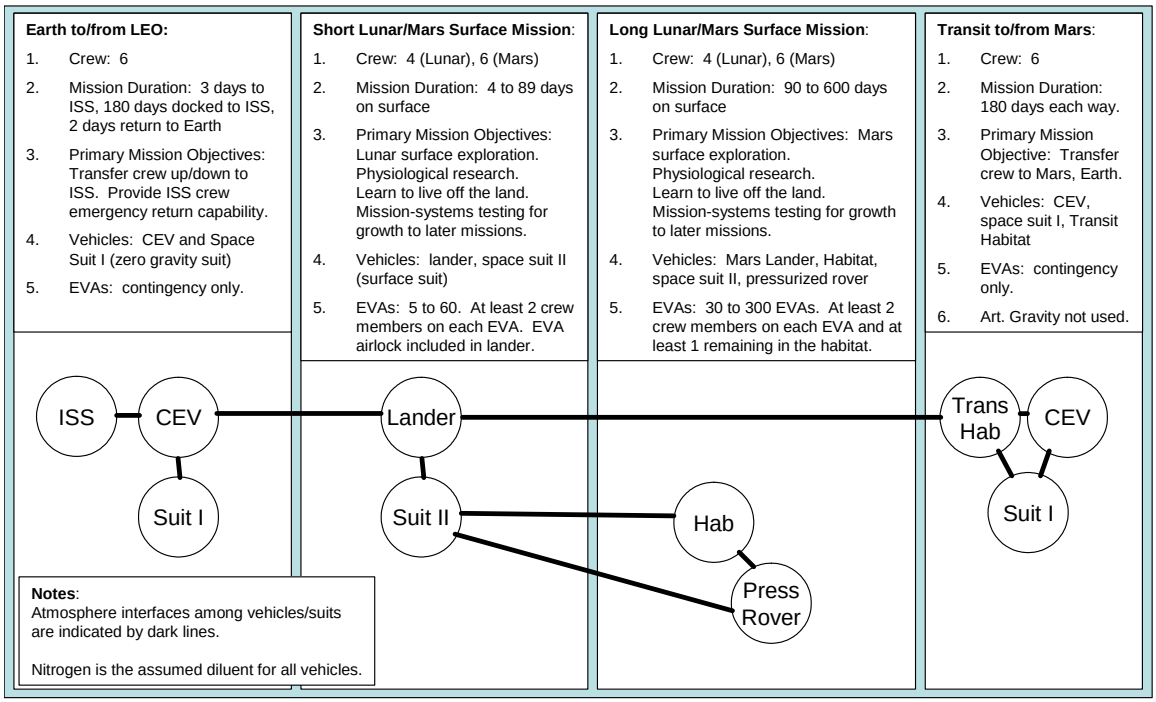


Figure 4.2-1 EAWG Mission-Systems Assumptions

The Analytical Hierarchy Procedure (AHP) was used as a tool to survey the 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 the meeting to generate an EAWG cumulative ranking across all three discipline subgroups. This culminated in the weighted rankings illustrated in Table 4.2-1. The numbers in the cells of the table are the candidate atmosphere design points described in Table 4.1-1.

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 4.2-1 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 candidate atmosphere design points described in Table 4.1-1.

To further analyze and detail significant findings and issues related to atmosphere design, EAWG members generated white papers on several topics that are listed in Table 4.2-2. These papers are included in Appendix E. They were made available prior to the workshop to give outside reviewers a deeper understanding of the various issues being addressed by the EAWG.

Table 4.2-2 EAWG White Paper Topics

Number	Topic
1	Ambulation During Extravehicular Activity on Moon and Mars as a Risk Factor for Decompression Sickness
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.
  - There is significant uncertainty on 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.
  - Has higher programmatic risk that requires engineering to minimize mass and achieve required reliability for surface EVAs.
  - Has 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, including additional materials testing (additional program cost).
  - There may be added operational restrictions related to items such as crew clothing.

In addition, quantitative breakpoints for analysis were identified as follows:

- 30% oxygen is the maximum flammability test level for ISS/Shuttle Programs,
- 70% and 100% oxygen were used operationally by past human programs,
- 1 hr prebreathe is a reasonable maximum time for operations and physiology,
- 3.5 psia suit pressure is a reasonable minimum based on physiology,
- 6 psia suit pressure is a reasonable operating maximum based on engineering capability.

Gap analysis was also performed by the EAWG. The EAWG August meeting included definition of research and technology needs related to atmosphere selection and its impacts on humans, vehicles, and space suits. The white papers included additional information on these areas of needs, as well as engineering challenges, that were then captured in the gap analysis.

After the analytical processes described above were conducted, the EAWG synthesized a tenth candidate atmosphere design point to use as a reference design at its workshop, so 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 EAWG's final recommendation and was open to change based on the workshop results. Figure 4.2-2 illustrates this reference design, designated Point X. It 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 space suit 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.

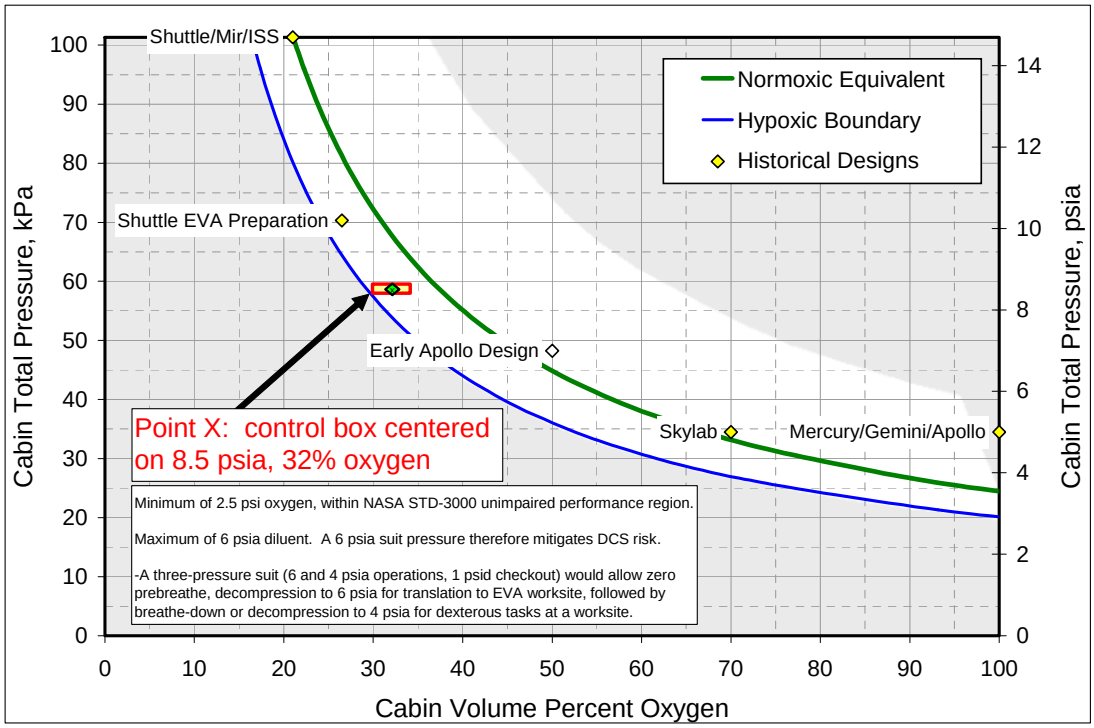


Figure 4.2-2 Workshop Reference Design Point X

The Exploration Atmospheres Workshop was held November 1-3, 2005 in Houston, Texas. The workshop report 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 US 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 to be exhaustive or prioritized. Table 4.2-3 lists human research areas, Table 4.2-4 lists technology development areas, Table 4.2-5 lists engineering challenges, and Table 4.2-6 lists expected programmatic impacts and opportunities for Constellation. It is noted that several items in Table 4.2-3 are already in the Bioastronautics Roadmap 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 space suit atmospheres. These are documented in Section 5 of this report.

Table 4.2-3 Human Research Areas

Research Question
What is the probability of DCS as a function of tissue ratio under microgravity, Moon and Mars partial gravity?
What is the most effective pre-EVA Decompression Sickness (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 technology, and how might they be adapted for reduced-G operations?
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?
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 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?
Burn treatment (external and inhalation) in reduced gravity

Table 4.2-4 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 O2% 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 non-flammable coverings and coatings for flammable materials
Methodology to assess total risk of fire to vehicle/habitat system
Food Processing: Development of an EMI 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 4.2-5 Engineering Challenges

Challenge
How do the different % O2 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 be susceptible to more failure modes.
Variable Pressure Suit: the impacts on decompression sickness 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 setpoint could be developed which "follows" the primary regulator set point changes. (see regulator challenge)
Variable Pressure Suit: Relief valve to enable quick reduction of the suit pressure to desired operating range function would be more difficult to implement in a variable pressure suit, as the final setpoints 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 (e.g. CO2 sensor).
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 in order to maintain a longer cycle life. Also, hard goods provide less adjustability (add parts mass) and are more expensive to design and manufacture, 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.
Materials Flammability: Composites and polymers proposed for space radiation control might have to be wrapped in non-flammable 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 COTS 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 4.2-6 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 prebreathe 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.

5.0 Recommendations for Mission Systems Design

This section captures major technical findings and recommendations resulting from the EAWG's trade study and closely related efforts. These recommendations are directed toward exploration programs within the Agency and specifically toward the Constellation Program. In addition, Section 6.0 provides recommendations on future NASA work related to atmosphere design and selection. The recommendations provided herein are not requirements and 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, in order to ensure crew safety, vehicle reliability, mission design flexibility, systems inter-operability, and crew operational efficiency.

As detailed in Table 5.1-1, the initial CEV, designated to provide crew transfers to the ISS, and the lunar and Mars CEVs should utilize 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.

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 utilize atmospheres of 8.0 and 7.6 psia (nominal). After extended acclimation of the surface habitat crewmembers, 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 suit 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, the Human Systems Integration Standards, Volume I, Revision B, Figure 5.1.2-2. The recommendations are based on the most recent, substantial physiological testing evidence that healthy individuals can perform reliably under the recommended conditions, including equivalent altitudes up to 8,000 feet (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 and Waligora et al., 1982).

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

Table 5.1-1 provides a summary of the recommendations to Constellation. Figure 5.1-1 illustrates how they relate to and integrate with each other. Figure 5.1-2 illustrates the recommended atmospheres in the context of historical NASA spacecraft designs.

Table 5.1-1 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 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	

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.
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: 10.2 psia recommendation is based on Shuttle experience, for CEV contingency EVA preparation.

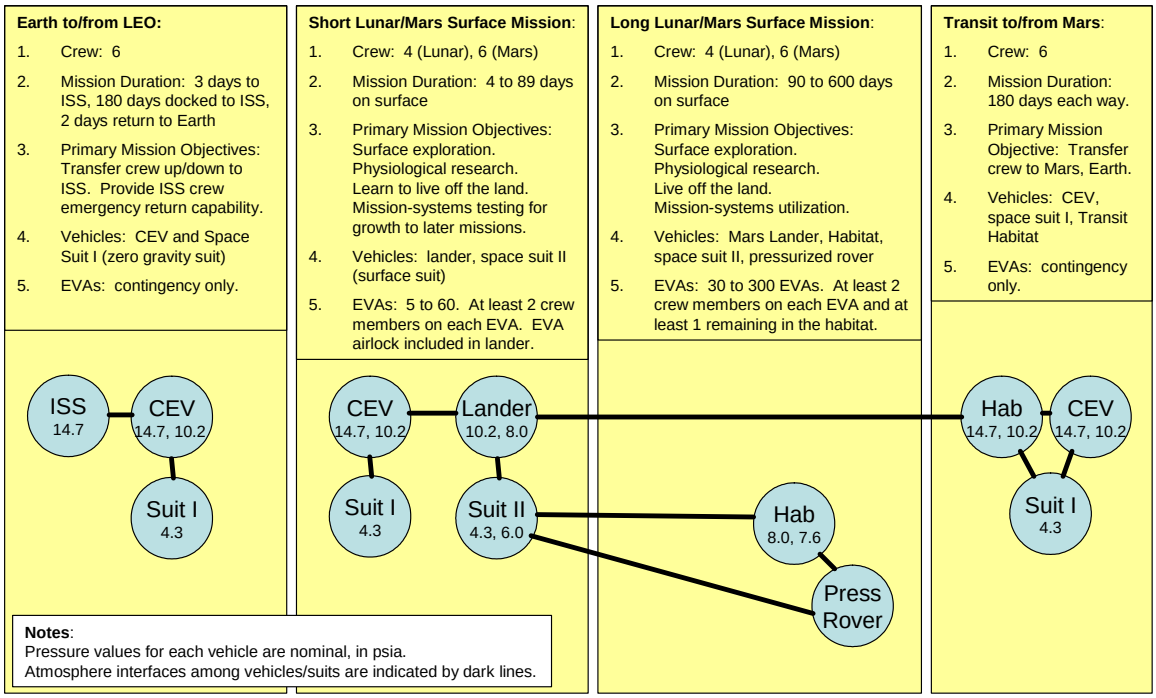


Figure 5.1-1 Integrated Atmosphere Recommendations for Constellation

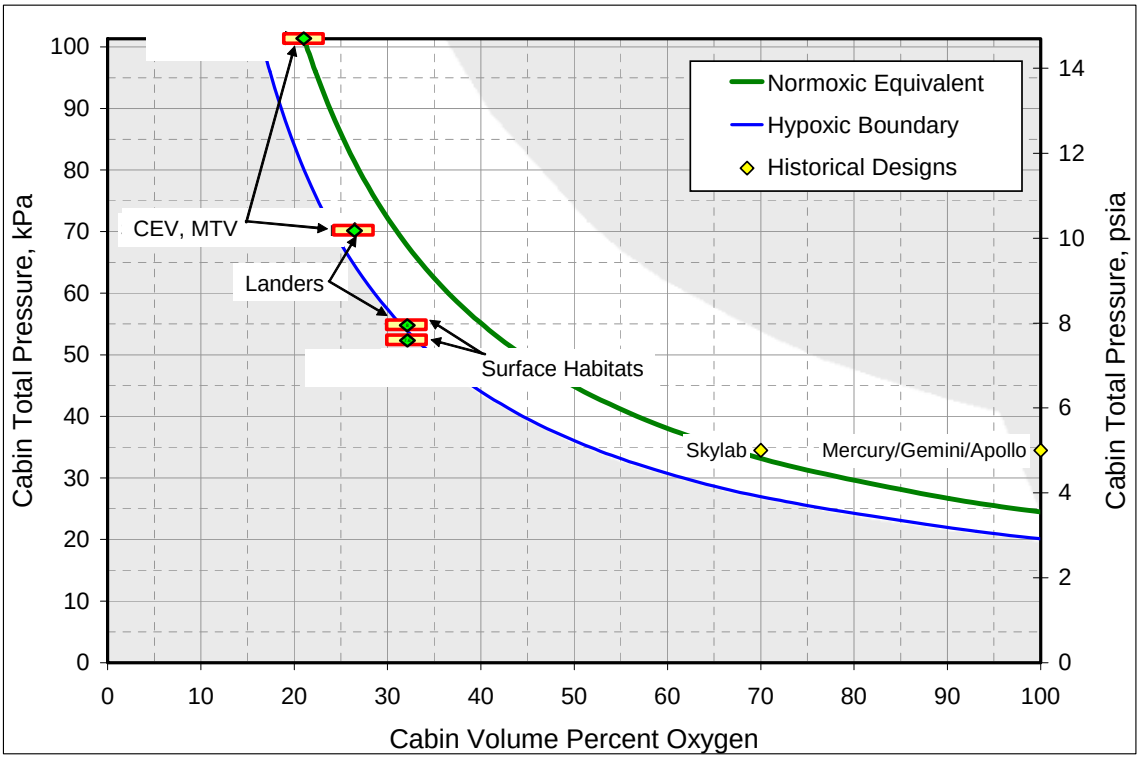


Figure 5.1-2 Historical Spacecraft and Recommended Constellation Atmospheres

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 5.1-3. The nominal total pressures, oxygen partial pressures, and oxygen concentrations given in Table 5.1-1 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 +/- 2 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.

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 Shuttle and ISS Programs have certified many materials for use at a maximum of 30% oxygen.

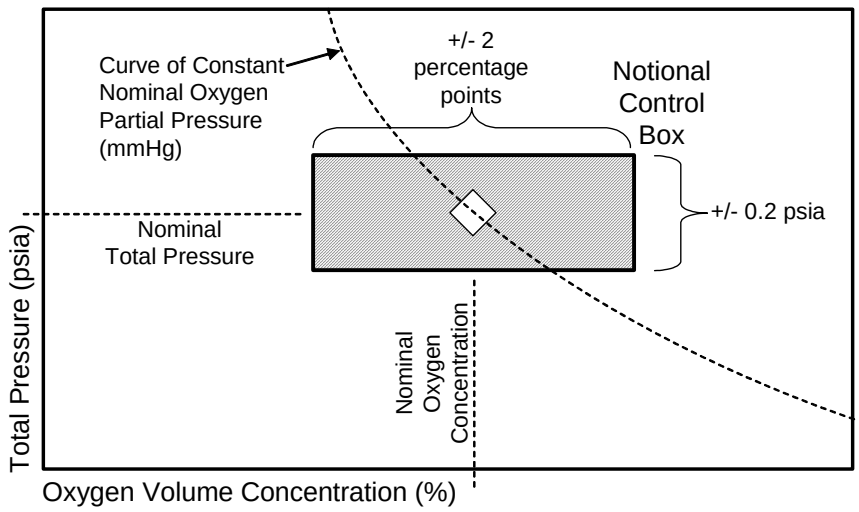


Figure 5.1-3 Notional Control Box for Vehicle Cabin Atmospheres

5.2 CEV to ISS

The initial CEV mission is intended to service the ISS with crew and cargo. Compatibility with the nominal ISS atmosphere of 14.7 psia, 21% oxygen and 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 5.1-1, 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 Agency health standards and within current system design regimes and allow the use of existing COTS hardware, clothing, stowage containers, etc. that are certified for flammability to Shuttle/ISS requirements.

5.3 CEV 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 PLSS atmosphere designs and attendant capabilities were considered by the EAWG to meet the needs of this suit. Per Table 5.1-1, 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 CEV

The CEV is also intended to function in both lunar and Mars crew transit missions. This CEV must interface with lunar and Mars vehicles including the lunar lander and the Mars transit vehicle. Per Table 5.1-1, 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 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 5.1-1, the lunar and Mars landers are recommended to use both a 10.2 psia 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 internal structure.

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

5.6 Lunar and Mars Surface Suits

The surface suit is intended to provide for multiple, low-overhead EVA capability on the planetary surface. The available development schedule for this suit places emphasis on 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 5.1-1, the lunar and Mars surface suits are recommended to use atmospheres of 4.3 and 6.0 psia to provide flexibility in EVA preparation and EVA operations. 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. 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. 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 5.1-1, the lunar and Mars Habitats are recommended to use both 8.0 psia 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 development of 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 and 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 5.1-1, the Mars transit vehicle is recommended to initially operate at 14.7 psia 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.

6.0 EAWG 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's technical results for Constellation mission-systems design and implementation.

6.1 Human Research Program

The EAWG recommends that the Human Research Program consider research in the areas listed in Table 4.2-3. This research would support the Office of the Chief Health and Medical Officer (OCHMO) in development of Agency-level human health, medical, and environmental standards and Constellation in development of lunar and Mars mission capabilities. It is noted that several similar research questions are currently in the Bioastronautics Roadmap.

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 4.2-4, to support Constellation in development of lunar and Mars missions.

6.3 Constellation Program

The EAWG recommends that Constellation perform program-specific trade studies to evaluate this report's atmosphere recommendations, in order 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 prebreathe time, and the non-metallic materials development/ test/ certification/ usage control process.

The EAWG recommends that the Constellation Program perform systems engineering to address the areas listed in Table 4.2-5. The EAWG also recommends that the Constellation Program study the issues and potential programmatic impacts (e.g. cost, schedule, definition of acceptable risk) listed in Table 4.2-6.

Because of the uncertainties in the final maximum oxygen percentage concentration to be used, as soon as possible Constellation should modify the standard NASA flammability

test 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 the NASA groups involved in materials flammability testing begin to plan for certification testing at increased oxygen concentration levels in future testing.

6.4 CEV Project

The EAWG recommends that the CEV Project support the atmosphere trade study described in section 6.3. CEV should also incorporate findings from 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 landers and surface habitats must be conducted to insure 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.

7.0 References

Balldin U, J Webb, R Tutt, D Wheeler, J Fischer, W Thompson, et al. Effect of Low Grade Hypoxia at Night in Special Operations Forces Aircraft Operations. AFRL-HE-BR-TR-2005-0163, Biosciences and Protection Division, Brooks City-Base, San Antonio, Texas, November 2005.

Lange KE, AT Perka, BE Duffield, FF Jeng, Bounding the Spacecraft Atmosphere Design Space for Future Exploration Missions, NASA/CR-2005-213689, 2005.

NASA, Biomedical Results of Apollo, NASA-SP-368, 1975.

NASA, Human Systems Integration Standards, NASA-STD-3000, Volume I, Revision B, 1995.

NASA, Space Flight Health Requirements Document, JSC 26882, 1996.

NASA, Flammability, Odor, Offgassing and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion, NASA-STD-6001, 1998.

NASA, The Vision for Space Exploration, 2004.

NASA, Bioastronautics Roadmap, NASA- SP-2005-6113, 2005.

NASA, Exploration Systems Architecture Study (ESAS) Final Report, NASA-TM-2005-214062, 2005.

NASA, Human-Rating Requirements for Space Systems, NPR 8705.2A, 2005.

NASA, JSC Design and Procedural Standards, JPR 8080.5, Revision A, 2005.

Waligora JM, DJ Horrigan, Jr, MW Bungo, J Conkin. Investigation of Combined Effects of Bedrest and Mild Hypoxia. Aviat. Space Environ. Med. 1982; 53(7):643-46.

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Appendix B: EAWG Implementation Plan

Appendix C: EAWG Fault Tree Analysis

Appendix D: EAWG Analytical Hierarchy Analysis

Appendix E: EAWG White Papers

Appendix F: EAWG Workshop Report

Appendix A: EAWG Members

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Jones, Jeff	Code SD, NASA JSC
Khan-Mayberry, Noreen	Code SF23, NASA JSC
Lange, Kevin	Jacobs Sverdrup Technology
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