

SSP 2006 TEAM PROJECT

# LUNA GAIA

A closed-loop habitat for the moon

FINAL REPORT





LUNA GAIA:  
A CLOSED LOOP HABITAT FOR THE  
MOON

Final Report

International Space University  
Summer Session Program 2006

The 2006 Summer Session Program of the International Space University was hosted at the International Space University Central Campus, France.

Artwork designed by: Jonathan J. O' Regan with support from [Sarah Jane Pell](#). Source Collage images courtesy of [NASA Johnson Space Center \(NASA-JSC\)](#), [NASA Glenn Research Center \(NASA-GRC\)](#) and [CoolText](#).

While all care has been taken in the preparation of this report, it should not be relied on, and ISU does not take any responsibility for the accuracy of its content.

Additional copies of the Executive Summary, Report and project CDs may be ordered from the International Space University Central Campus and can also be found on the ISU Web site. Ordering information, order form and electronic files may be found on the ISU web site at <http://www.isunet.edu>



International Space University  
Strasbourg Central Campus  
Attention: Publications/Library  
Parc d'Innovation  
1 rue Jean-Dominique Cassini  
67400 Illkirch-Graffenstaden  
France  
Tel. +33 (0)3 88 65 54 32  
Fax. +33 (0)3 88 65 54 47  
e-mail. [publications@isu.isunet.edu](mailto:publications@isu.isunet.edu)

---

## Dedication

We, the students of the International Space University Summer Session Program 2006, wish to dedicate our work to the memory of Morla Milne who died unexpectedly on August 11, 2006 in Strasbourg, at the age of 33.

Morla began her relationship with ISU as we have. She was a SSP'99 student in Thailand before becoming a Teaching Associate in 2000 in Chile. Since then she supported the students as the Assistant Director of Academics at ISU.

Morla's vision and passion motivated us all upon our arrival in Strasbourg. Now her legacy is a source of inspiration for us all as we continue our ISU experience and move on thereafter.

Our hearts go to her brother, Brad.



## Acknowledgements

The International Space University Summer Session Program 2006 and the work on the Team Project were made possible through the generous support of the following organizations and individuals:

### PROJECT SPONSOR

NASA Ames Research Center, USA

















### PROJECT FACULTY AND TEACHING ASSOCIATES

















Co-Chair	Dr. Simon P. Worden, NASA Ames Research Center, USA
	Dr. Alan Weston, NASA Ames Research Center, USA
	Dr. William Marshall, NASA Ames Research Center, USA
Faculty Shepherd	Dr. Mikhail Marov, Russian Academy of Science, ISU Faculty
Teaching Assistant	Jessica Scott, Cardiovascular Physiology and Rehabilitation Laboratory, Canada
	Alexander Ivanov, ISU Central Campus, France
Staff Advisor	Axelle Cartier, Leiden University, Netherlands
	Carol Carnett, Legal Aid Bureau of Maryland, USA
	Fabio Sau, University of North Dakota, USA

### External Experts

Hugo Blomfield	City of Vancouver, Canada
Lin Copeland Burke	ISU Staff, USA
Dr. Ignasi Casanova	Polytechnical University of Catalonia, Spain
Dr. Bernard Foing	European Space Agency, France
Dr. Gene A. Giacomelli	University of Arizona, USA
Dr. Jeff Hoffman	Massachusetts Institute of Technology, USA
Dr. Jeffery Jones	NASA Johnson Space Centre, USA
Fathi Karouia	University of Houston, USA
Cheryl Kennedy	National Renewable Energy Laboratory, USA
Dr. Mark H. Kliss	NASA Ames Research Center, USA
Michael Loweth	Ministry of Defense, UK
Brent McConnell	SED Systems, Canada
Dr. M.C. Natori	Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA)
Vidar Ovrebo	OmegaH2 Ltd, Norway
Philip D. Sadler	Sadler Machine Co., USA
Dr. Didier Schmitt	European Space Agency – ESTEC, Netherlands
Berin Michael Szoka	Institute for Space Law and Policy, USA
Dr. Paul Todd	Space Hardware Optimization Technology, Inc., USA
Dr. Bruce Webbon	NASA Ames Research Center, USA



<p><b>Alfredo Agenjo</b> M. Sc. Aeronautical Engineer</p>		<p>Spain</p>		<p><b>Masataro Amano</b> Graduate Student, Smart Material Engineer, University of Tokyo</p>
<p><b>Simon Auclair</b> Student, Geologist</p>		<p>Canada</p>		<p><b>Francesc Betorz</b> M.Sc. Civil Engineer PhD Candidate</p>
<p><b>James Chartres</b> Postgraduate Student , The University of Adelaide</p>		<p>Australia</p>		<p><b>Yibing Deng</b> Senior Engineer, ACC</p>
<p><b>Stephen Eisele</b> Senior Analyst , DFI International</p>		<p>USA</p>		<p><b>Martin Gagnon</b> Chiropractor, Centre Chiropratique Chambly</p>
<p><b>Natalie Galley</b> PhD Candidate, Aerospace Engineering</p>		<p>Canada</p>		<p><b>Nil Garcia</b> Telecommunications Engineer</p>
<p><b>Jean-Francois Gauthier</b> Advanced Member of Technical Staff, COMDEV</p>		<p>Canada</p>		<p><b>Tracy Gill</b> Integration Engineer, NASA</p>
<p><b>Kieran Griffith</b> BSc Aerospace Studies, Embry Riddle Aeronautical University, Mars Society</p>		<p>Ireland</p>		<p><b>Zhonglai Guo</b> Senior Engineer, JSLC</p>
<p><b>Daryn T. Harkins</b> Systems Engineer, The Boeing Company</p>		<p>USA</p>		<p><b>David T. Haslam</b> MSc. University of Manchester Laser Physicist Space Generation Network</p>

<b>Kwan Ting Ho</b> Microbiology & Immunology, McGill University; Law, University of Pennsylvania	 Canada	 Canada	<b>Adam King</b> University of British Columbia; Communications Manager, See-Breeze Power Corp.
<b>Violetta Kuvaeva</b> External Economic Activity, Moscow Aviation University,	 Russia	 Canada	<b>Scott MacPhee</b> ISU Masters Student
<b>Hugues Wilfrid Mbezal</b> Mechanical Systems Engineer Project Manager, CNES Europe's Spaceport, Kourou	 France	 USA	<b>Michelle Murray</b> Aerospace Engineer, Office of Commercial Space Transportation Federal Aviation Administration
<b>Padraig O' Gallachoir</b> Mechanical Engineer	 Ireland	 Ireland	<b>Jonathan J. O' Regan</b> Architect; Physics Student, University of Wales, Aberystwyth
<b>Noriyuki Onoue</b> Graduate Student, Molecular Biology, Hokkaido University	 Japan	 USA	<b>Shabnam Ozlati</b> Graduate Student, Human Factors, California State University
<b>Sara Jane Pell</b> PhD. Artist, Aquanaut	 Australia	 Canada	<b>Sara Poirier</b> Astronomer & Space Scientist, Ontario Science Center
<b>Hidemi Takahashi</b> Graduate Student, Propulsion Engineering Tohoku University	 Japan	 Japan	<b>Yumiko Tateshita</b> Legal Associate, Japan Aerospace Exploration Agency
<b>Erin Tranfield</b> PhD Candidate, The James Hogg iCAPTURE Center	 Canada	 Belgium	<b>Jeroen Vandersteen</b> Mechanical Engineer



Luna Gaia posits a pathway towards new technologies, philosophies, systems applications and infrastructure aimed at achieving a closed loop habitat model for human settlement on the Moon. This report makes recommendations pertaining to the systems architecture, engineering processes, and the research, development and orchestration of separate phased precursor missions which will be required to achieve this vision by the year 2030. The framework that we propose is designed to support an ideal profile of an optimum 11 (maximum 12) member human crew on the lunar surface for a period of 18 - 36 months.

The Luna Gaia design solutions focus on the coupling power for all regenerative processes of a network of closed loop life support. Using proven and innovative solutions that produce relatively independent and highly reliable cycles of oxygen, water, energy, food growth and waste processing, the modular, hybrid bio-regenerative network of systems particular to the Luna Gaia design architecture is ambitious but feasible.

This report also details ethical and philosophical considerations of lunar settlement and the wider implications for international law, policy and future interplanetary social governance. The authors intend to evolve the current status of thought and practice on these issues to consider new and responsible configurations of resource assets - on Earth and the Moon - and to inspire the will and confidence necessary to propel humanity, and its technology, towards the next frontier of lunar settlement. The management principles are sound, the Earth-based applications are considered and the legal frameworks have been clearly defined. Certain risks are apparent but there are significant opportunities and benefits which will occur. More importantly, the project vision is consistent with the preservation of life and responsible evolution into the solar system.

We appeal to interested agencies and research organizations to support the Luna Gaia Vision and to encourage author participation in advancing these mission studies.

Luna Gaia affirms our commitment to global participation in the extension of human presence on the Moon, and beyond...

The 2006 International Space University (ISU) Summer Session Program (SSP) was held during July and August in Strasbourg, France at the ISU campus. The SSP brought together graduate students and space professionals from all over the world and immersed them in an intensive nine-week, interdisciplinary, intercultural and international curriculum of lectures, workshops, site visits and research.

A key component of every SSP is the Team Project in which the students produce a space project on a topic of international relevance. In 2006 three different Team Projects were undertaken. This report contains the findings of one of them: Luna Gaia, a project to design a habitat for 11-12 people to live for periods of up to 36 months on the Moon to be built by 2030.

The team consisted of 32 people from 12 countries (Australia, Belgium, Canada, China, France, Iran, Ireland, Japan, Russia, Spain, UK and US) and four continents. Luna Gaia was supported by space experts from around the world, both inside and outside the ISU community.

The objectives of the project were to:

- Identify and evaluate the location for, design of, and implication of a lunar habitat.
- Produce a report that can influence future international planning and execution of lunar space exploration programs.
- Provide experience in multidisciplinary teamwork, under pressure of limited time and resources, on a problem of current world importance.

During the project the team analyzed the current state of knowledge of the Moon resources and environment, performed an overall design of one habitat and gave an overview of the legal, political, budgetary and philosophical implications of the design. The design of the first lunar habitat is a half-way step from human sorties to the self-sustainable settlement off-Earth, a significant milestone for humanity. The study provides an important contribution of the overall design of a lunar habitat: elaborating one specific design scenario of how we might go forward.

We, the team faculty and teaching associates, are pleased to commend both the team and its report to you. We highly recommend that the study be assessed by space agencies and used in the near term to help to adjust the plans for the existing phase of lunar exploration to take into account the needs of the habitat phase to follow.

It has indeed been a pleasure to work on this project with such a professional, smart and dedicated team.

Pete Worden  
Co-chair  
NASA-Ames, USA

Alan Weston  
Co-chair  
NASA-Ames, USA

Will Marshall  
Co-chair  
NASA-Ames, USA

## Student Preface

---

*"I should venture to assert, that if these worlds are habitable, they either are, have been, or will be inhabited."*

- Jules Verne, From the Earth to the Moon, 1877

People have always been fascinated by space and the Moon. That is exactly what brings our team together; a team with 32 very different people, representing 12 different nationalities, different cultures and different backgrounds. We all love space. It was not easy to work together in this heterogeneous group. Our team members speak different languages, come from different cultures, have different opinions, different personalities and different styles. We always had too little time to do too many things. But we did it! And we did it as a team. We produced an innovative report which will bring us a little closer to the Moon.

This report discusses a closed loop lunar habitat from different perspectives. The physical sciences, engineering and life sciences aspects are examined, as well as the policy, law, business and management that enable this ambitious project.

It was not only our enthusiasm that kept us going. We had help from many people at the International Space University and our colleagues from industry. Our lovely TA's: Jessica Scott and Alexander Ivanov made our life easier. Or was it the after-hour meetings with Pete Worden that were responsible for our great team spirit and creativity? Mikhail Marov provided us with his knowledge and expertise in various fields. Last but not least, we would like to thank the enthusiasm of Alan Weston, and Will Marshall for their great support, and of course, all the people at ISU who made this possible.

TP Luna Gaia  
Strasbourg 2006



---

## Recommendations

---

We recommend to space agencies the following near-term steps, (that are not currently being undertaken), in order to prepare for a human habitat on the Moon:

### *Precursor Space Missions*

- Test modular and inflatable habitat designs and building materials in analogue and *in situ*.
- Test the viability of foam panel creation for solar power generation on the Moon.
- Develop and test extraction processes with different gases, energy requirements, as well as *in situ* concentrations of minerals at the chosen location.
- Locally map the potential habitat locations using robotic landers.
- Characterize the dust in the lunar exosphere.
- Research the surface electric field height profile to consider the surface potential and the shielding scale length.
- Establish an international scientific working group and taskforce to be responsible for recommending networked instrumentation and protocols for lunar exploration.

### *System Development*

- Develop an interface adapter between Soyuz and the planned lunar surface access module (LSAM) to provide an alternate crew rescue vehicle.
- Develop an alternate human-rated lunar lander to provide an alternate to LSAM.
- Develop a standard commercial lunar lander and transfer stage to get cargo from LEO to the lunar surface and thus allow for commercial and international low cost launch options.
- Commence extensive testing of solar thermal power generation to prove viability as a long-term energy source.
- Explore the use of fission reactor power systems during pre-launch, launch, mission operation and post-operation phases to test viability and safety.

### *Advanced Research and Development*

- Continue research into the physiological effects of chronic dust and radiation exposure.
- Develop and test Mechanical Counter Pressure (MCP) space suits.
- Research material technologies to be used in seals for airlocks and containers.
- Research contamination prevention and sterilization measures.
- Explore the use of extremophile genes to splice and terraform the lunar regolith for oxygen.
- Research the integration of fungi and insects as a subsystem in artificial closed ecosystems.

### *Policy, Law, Philosophy*

- Develop an international and cross-cultural forum to investigate the strengths of different economic, social and political systems that could be used on the Moon.
- Create a clear-cut property rights regime that encourages and secures private investment.
- Create an international space exploration agency to coordinate lunar missions of national space agencies.
- Research the rationale and ethics particular to the current legal frameworks and how they may need to be adapted for the specific considerations of lunar settlement.
- Develop lunar sample containment, archival preservation and handling protocols.
- Increase education, outreach, public participation, access to information and opportunities for open dialogue on space missions.

<b>INTRODUCTION AND SUMMARY .....</b>	<b>1</b>
1.1 MISSION STATEMENT .....	2
1.2 CONCEPT OF OPERATIONS .....	2
1.3 OVERALL DESIGN CONCEPT .....	6
1.3.1 Architecture Design.....	6
1.3.2 Closed loop life support systems (CLLSS).....	7
1.3.3 Health .....	7
1.3.4 Location.....	7
1.3.5 In-Situ Resource Utilization (ISRU).....	7
1.3.6 Enabling Framework.....	7
1.3.7 Policy.....	8
1.3.8 Law.....	8
1.3.9 Power .....	8
<b>2 MISSION PLANNING REQUIREMENTS .....</b>	<b>9</b>
2.1 REQUIREMENTS .....	9
2.2 LOCATION.....	10
2.2.1 Location Considerations .....	10
2.2.2 Lunar Resources and Soil Composition .....	10
2.2.3 In Situ Resource Utilization .....	10
2.2.4 Lunar Regions .....	12
2.3 POWER .....	14
2.3.1 Power budget.....	14
2.3.2 Power Generation Options.....	16
2.3.3 Primary Power Generation .....	18
2.3.4 Secondary Power Generation.....	21
2.3.5 Primary Power Storage & Regulation .....	22
2.3.6 Secondary Power Storage .....	22
2.4 TRANSPORTATION .....	23
2.4.1 Earth to Moon .....	23
2.4.2 Build Philosophy .....	24
2.4.3 Other Transportation Needs.....	26
2.4.4 Recommendations.....	28
<b>3 CLOSED LOOP HABITAT DESIGN .....</b>	<b>29</b>
3.1 DESIGN ARCHITECTURE .....	29
3.1.1 Construction Type .....	29
3.1.2 Construction Technologies.....	32
3.1.3 Protection .....	34
3.1.4 Incorporation of Closed Loop Systems.....	36
3.1.5 Infrastructure.....	39
3.1.6 Design Considerations .....	39
3.2 CLOSED LOOP LIFE SUPPORT SYSTEMS .....	41
3.2.1 Introduction.....	41
3.2.2 Human Requirements .....	42
3.2.3 Specific Methods for CLLSS Technologies: ECLSS Technologies.....	47



3.2.4	<i>Air</i> .....	48
3.2.5	<i>Water Methods</i> .....	52
3.2.6	<i>Food Methods</i> .....	53
3.2.7	<i>Previous Closed Loop Life Support System Efforts</i> .....	55
3.2.8	<i>Recommended Solution: Luna Gaia Life Support System (LuGaLiSuS)</i> .....	58
3.2.9	<i>Redundancy</i> .....	63
3.2.10	<i>Physico-Chemical Back-Up Systems</i> .....	63
3.2.11	<i>Recommendations for Research</i> .....	66
3.3	<b>HEALTH</b> .....	68
3.3.1	<i>Physical Well-Being of the Residents</i> .....	69
3.3.2	<i>Physical Countermeasures</i> .....	69
3.3.3	<i>Personal and Social Well-Being of the Residents</i> .....	70
3.3.4	<i>Behavior-Shaping Constraints on the Closed Loop Habitat and Lunar Environment</i> .....	71
3.3.5	<i>Psychological Countermeasures and Mitigations</i> .....	72
3.3.6	<i>Tests and Evaluations</i> .....	74
3.4	<b>RADIATION</b> .....	74
3.4.1	<i>Radiation Sources</i> .....	74
3.4.2	<i>Human Consequences of Radiation Exposure</i> .....	75
3.4.3	<i>Approaches to Risk Mitigation</i> .....	77
3.5	<b>SAFETY</b> .....	81
3.5.1	<i>Lunar Dust</i> .....	81
3.5.2	<i>Fire</i> .....	82
3.5.3	<i>Temperature Extremes</i> .....	83
3.5.4	<i>Contamination</i> .....	83
4	<b>PHILOSOPHICAL AND SOCIETAL ISSUES</b> .....	87
4.1	<b>SURVIVAL OF THE EARTH'S BIOSPHERE AND THE HUMAN SPECIES</b> .....	87
4.1.1	<i>Prosperity</i> .....	88
4.1.2	<i>Curiosity: The Quest for Knowledge</i> .....	88
4.1.3	<i>Growth: New Habitats for Life and New Frontiers</i> .....	89
4.2	<b>ETHICS</b> .....	89
4.2.1	<i>Philosophical Framework</i> .....	89
4.2.2	<i>Human Rights</i> .....	90
4.2.3	<i>Gaia Ethics</i> .....	90
4.2.4	<i>Sovereignty and Power</i> .....	90
4.2.5	<i>Risks</i> .....	90
4.3	<b>SOCIAL GOVERNANCE</b> .....	91
4.4	<b>SUSTAINABLE MANAGEMENT</b> .....	92
4.4.1	<i>Access to Data</i> .....	92
4.4.2	<i>Geophysical Network Instruments</i> .....	92
4.4.3	<i>Communication and Information System</i> .....	93
4.4.4	<i>Mission Documentation</i> .....	93
4.4.5	<i>Protection Taskforce</i> .....	93
4.4.6	<i>Education, outreach, information and mediation pedagogy</i> .....	93
4.5	<b>FUTURE IN SPACE</b> .....	94
4.5.1	<i>Lunar Helium-3 as an Energy Source</i> .....	94
4.5.2	<i>Future Mission to Mars and Beyond</i> .....	95
5	<b>POLICY ISSUES</b> .....	97
5.1	<b>OBJECTIVES OF SOUND POLICY</b> .....	97
5.1.1	<i>Political</i> .....	97

5.1.2	<i>Economic</i> .....	97
5.1.3	<i>Scientific</i> .....	98
5.1.4	<i>Societal</i> .....	98
5.1.5	<i>Critical Path for Policy</i> .....	98
5.2	GOVERNING BODY .....	98
5.2.1	<i>Governing Models</i> .....	99
5.2.2	<i>Recommendations</i> .....	99
5.3	PAVING THE PATH FOR PRIVATE INVOLVEMENT .....	100
5.3.1	<i>Property Rights</i> .....	100
5.4	EXPORT CONTROLS REGULATIONS .....	102
5.4.1	<i>Export Control Regimes</i> .....	103
5.4.2	<i>Example: ITAR</i> .....	103
5.4.3	<i>Recommendations</i> .....	103
5.5	PLANETARY PROTECTION .....	104
5.5.1	<i>Quarantine of Martian Samples</i> .....	105
5.5.2	<i>Recommendations</i> .....	105
5.6	NUCLEAR POWER .....	105
5.6.1	<i>Adverse Safety, Environmental, and Health Risks</i> .....	106
5.6.2	<i>Potential Security Risks</i> .....	106
5.6.3	<i>Nuclear Waste</i> .....	106
<b>6</b>	<b>LEGAL ISSUES</b> .....	<b>107</b>
6.1	LEGAL FRAMEWORK .....	107
6.1.1	<i>Existing Legal Framework</i> .....	107
6.2	OBSOLESCENCE OF THE MOON AGREEMENT .....	108
6.3	EXAMINATION OF INTERNATIONAL SPACE STATION LEGAL FRAMEWORK .....	108
6.4	LUNA GAIA'S LEGAL FRAMEWORK .....	112
6.4.1	<i>Inter-Governmental Cooperation</i> .....	113
6.4.2	<i>Cooperation Between Governments and Other Partners</i> .....	114
6.4.3	<i>Contamination and Pollution</i> .....	114
6.4.4	<i>Conclusions and Recommendations</i> .....	115
<b>7</b>	<b>ECONOMIC ISSUES</b> .....	<b>117</b>
7.1	BUDGET .....	117
7.1.1	<i>Introduction</i> .....	117
7.1.2	<i>International Cooperation</i> .....	117
7.1.3	<i>Private Investment</i> .....	118
7.1.4	<i>Technical Cost Assessment of Luna Gaia</i> .....	118
7.2	PUBLIC-PRIVATE PARTNERSHIP OPTIONS .....	121
7.2.1	<i>Partnering for Success</i> .....	121
7.2.2	<i>Government Participation</i> .....	122
7.2.3	<i>Private Participation</i> .....	123
7.3	RISK MANAGEMENT/INSURANCE, INDEMNIFICATIONS, LIABILITY .....	126
7.4	COMMERCIALIZATION .....	127
7.4.1	<i>Private Sector Efficiency</i> .....	127
7.4.2	<i>Private Interests on the Moon</i> .....	127
7.5	PUBLIC RELATIONS .....	129
<b>8</b>	<b>EARTH APPLICATIONS</b> .....	<b>131</b>
8.1	IMPORTANCE OF EARTH APPLICATIONS .....	131
8.2	A CASE STUDY IN BIOPROCESSING: THE MEMBRANE BIOREACTOR .....	131

8.2.1	<i>Photon Collection and Delivery</i> .....	132
8.2.2	<i>Growth Media Transport System</i> .....	132
8.2.3	<i>Organism Harvesting and Repopulation</i> .....	133
8.2.4	<i>Improving Air Quality on Earth</i> .....	133
8.3	<b>OTHER POTENTIAL APPLICATIONS</b> .....	133
8.3.1	<i>Food Production</i> .....	133
8.3.2	<i>Contamination Technologies and Prevention</i> .....	134
8.3.3	<i>Water Filtration</i> .....	134
8.3.4	<i>Mining Techniques and Technologies</i> .....	134
8.3.5	<i>Power Generation</i> .....	134
8.3.6	<i>Testing Innovative Social, Political and Economic Processes</i> .....	135
9	<b>CONCLUSION</b> .....	<b>137</b>
10	<b>REFERENCES</b> .....	<b>139</b>

Figure 1.2-1 Luna Gaia Architecture Roadmap Timeline .....	3
Figure 1.2-2 Luna Gaia Mass Calculations .....	5
Figure 2.2-1 Lunar Soil Composition Composition (Averaged Over Entire Surface) .....	10
Figure 2.2-2 250 Km-Wide Image of Lunar North Pole Taken from SMART-1 .....	13
Figure 2.2-3 Recommended Habitat Location (Regional map).....	13
Figure 2.3-1 Comparison of Different Methods for Energy Storage.....	17
Figure 2.4-1 Launch Strategy .....	24
Figure 3.1-1 Lunar Location Options at Polar Latitudes .....	29
Figure 3.1-2 Expandable Design .....	31
Figure 3.1-3 Buckminsterfullerene or ‘Bucky-ball’ .....	31
Figure 3.1-4 Radiation Protection .....	35
Figure 3.1-5 i) Closed Loop Water Cycle Integration. ii) General Closed Loop Water Cycles .....	38
Figure 3.1-6 Infrastructure.....	39
Figure 3.1-7 Modular Human Dimensions (Le Corbusier). .....	40
Figure 3.1-8 Zoning diagram.....	40
Figure 3.1-9 Social Focus.....	41
Figure 3.2-1 Human Requirements Per Day .....	42
Figure 3.2-2 Human Tolerance Time of Oxygen Partial Pressure .....	44
Figure 3.2-3 Human Tolerance Time of Carbon Dioxide Partial Pressure .....	45
Figure 3.2-4 Human Tolerance Time to Temperature and Humidity.....	45
Figure 3.2-5 Human Comfort Levels to Temperature and Humidity .....	46
Figure 3.2-6 The MELiSSA cycle diagram.....	57
Figure 3.2-7 LuGaLiSuS System Block Diagram .....	60
Figure 3.2-8 Re-supply Mass Required for Level of Closed Loop Systems ...	64
Figure 3.4-1 BFO Dose-Equivalent for GCR at Solar Minimum for Various Materials .....	78
Figure 6.4-1 Luna Gaia’ s Legal Framework .....	113
Figure 7.1-1 NASA’s ESAS Overall Research and Technology Budget Broken Down by Mission .....	120
Figure 7.2-1 Public-led PPP Diagram .....	124
Figure 7.2-2 Private-led PPP Diagram .....	125

Table 2.1-1 Program Requirements.....	9
Table 2.2-1 Candidate Processes for Oxygen Production on the Moon.....	11
Table 2.2-2 Comparison of Lunar Regions .....	12
Table 2.3-1 Nominal Power Usage .....	14
Table 2.3-2 Minimum Power Usage .....	15
Table 2.3-3 Estimated Power Usage During Build-Up Phase.....	15
Table 2.3-4 Comparison of Power Generation Options .....	16
Table 2.3-5 Comparison of Photovoltaic Options.....	22
Table 2.4-1 Performance Comparisons of Launch Vehicles .....	23
Table 2.4-2 Mass and Launch Cost Estimate of Preliminary Phase.....	25
Table 2.4-3 Flight Logistics for Construction Phase.....	25
Table 2.4-4 Transportation Scheme for Luna Gaia .....	26
Table 2.4-5 Cost and Launch Ability Comparisons of Existing Vehicles.....	26
Table 3.1-1 Advantages and Disadvantages of Different Base Configurations .....	30
Table 3.1-2 Lunar Base Space Requirements.....	37
Table 3.2-1 Summary of Water Consumption per Crewmember for Different Operational States.....	43
Table 3.2-2 Human Atmospheric Requirements .....	43
Table 3.2-3 Lunar Atmosphere Design Requirements .....	44
Table 3.2-4 USDA Recommended Daily Intake by Food Group.....	47
Table 3.2-5 Degree of Achievement of Self-Sustainability.....	55
Table 3.2-6a: Proposed Daily Crew Diet .....	61
Table 3.2-6b: Nutritional requirements .....	61
Table 3.4-1 Expected Medical Effects Following Acute Radiation Exposure	76
Table 3.4-2. Recommended Organ Dose Equivalent Limits for All Ages.....	76
Table 3.4-3. LEO Career Whole Body Effective Dose Limits (Sv).....	76
Table 3.4-4 Shielding Requirements for 40 cSv.....	79
Table 7.1-1 International Partners Budget.....	118
Table 7.1-2 ESAS Detailed Estimated Budget Extrapolated from Figure 7.1-1 .....	120
Table 7.1-3 Luna Gaia Projected Cost Derived from ESAS Estimated Budget .....	121
Table 7.1-4 Deployment Cost for Lunar Settlement Mission with Luna Gaia .....	121

---

## List of Acronyms

---

2BMS	Two-Bed Molecular Sieve
4BMS	Four-Bed Molecular Sieve
<b>A</b>	
ACRS	Advanced Carbon Dioxide Reduction System
AES	Air Evaporation System
ALH84001	Allen Hills Meteorite 1984 number 1
Al	Aluminum
ALS	Advanced Life Support
Ar	Argon
ARS	Advanced Reduction System
ARS	Air Revitalization System
ASCR	Advanced System for Carbon Dioxide Reduction
atm	Atmosphere
<b>B</b>	
BCRS	Bosch Carbon Dioxide Reduction System
Bios-3	Biosphere-3
BLSS	Biological Life Support System
BSL-4	Stringent Biological Containment Facility
BWP	Biological Water Processor
<b>C</b>	
C	Carbon
C	Celsius
C <sub>6</sub> H <sub>12</sub> O <sub>6</sub>	Glucose
Ca	Calcium
Ca(O <sub>2</sub> ) <sub>2</sub>	Super Calcium Dioxide
CAES	Compressed Air Energy Storage
CaLV	Cargo Launch Vehicle (Ares V)
CAIB	Columbia Accident Investigation Board
CB	Canobacteria
CDE	Carbon Dioxide Electrolysis
CEBAS	Closed Equilibrated Biological Aquatic System
CELSS	Closed Environment Life Support System
CEV	Crew Exploration Vehicle
CFR	Carbon Formation Reactor
CFRP	Carbon Fiber Reinforced Plastic
CH <sub>4</sub>	Methane
CHP	Combined Heat and Power
Cl	Chlorine
CLLS	Closed Loop Life Support
CLLSS	Closed Loop Life Support System
CLS	Closed Loop System
CLV	Crew Launch Vehicle (Ares I)
CME	Coronal Mass Ejections
CO	Carbon Monoxide
CO <sub>2</sub>	Carbon Dioxide
CO <sub>3</sub> <sup>2-</sup>	Carbonate



COMEST	World Commission on the Ethics of Scientific Knowledge and Technology, Commission mondiale d'éthique des connaissances scientifiques et des technologies
COPUOS	Committee on the Peaceful Uses of Outer Space
COSPAR	Council for Science Committee on Space Research#
COTS	Commercial Off-The-Shelf
COTS	Commercial Orbital Transportation System
cSv	Centi-sieverts
<b>D</b>	
DNA	Deoxyribonucleic Acid
<b>E</b>	
ECG	Electrocardiogram
ECLSS	Environmental Control and Life Support System
EDC	Electrochemical Depolarized Concentrator
EIRS	Emergency Inflatable Radiation shelter
ESAS	Exploration Systems Architecture Study
ESRT	Exploration Systems Research and Technology
ESMD	Exploratory Mission Systems Directorate
EVA	Extra-Vehicular Activity
<b>F</b>	
F	Fluorine
Fe	Iron
FeO	Iron Oxide
FeTiO <sub>3</sub>	Ilmenite
FoOD	Fungus on Orbit Demonstration
FSPS	Fission Surface Power System
<b>G</b>	
g	Gram
GA	General Assembly
Ga	Gallium
GaAs	Gallium Arsenide
GaInP <sub>2</sub>	Gallium Indium Bi-Phosphate
GCR	Galactic Cosmic Rays
GDP	Gross Domestic Product
Ge	Germanium
GFRP	Glass Fiber Reinforced Plastic
GPS	Global Positioning System
GSA	General Services Administration
<b>H</b>	
H	Hydrogen
H <sub>2</sub>	Diatomic Hydrogen
H <sub>2</sub> O	Water
HCO <sub>3</sub>	Hydroxyformate
He	Helium
He <sup>3</sup>	Helium-3
HSRT	Human Systems Research and Technology
HTST	Hydro Therapy Storage Tank
HZE	Hazardous Particles
<b>I</b>	
IBAD	Ion-Beam-Assisted Deposition
ICPHS	International Council for Philosophy and Humanistic Studies
ICSU	International Council for Scientific Unions

IGA	Intergovernmental Agreement
IGPT	International Governmental Protections Taskforce
IMAG	International Multidisciplinary Artificial Gravity
IPN	InterPlaNetary (Internet Network)
ISEA	International Space Exploration Agency
ISRU	<i>In-Situ</i> Resource Utilization
ISS	International Space Station
ISSC	International Social Sciences Council
ISU	International Space University
ITAR	International Traffic in Arms Regulations
ITJ	Improved Triple Junction
IWRS	Integrated Water Recovery System
<b>J</b>	
JSC	Johnson Space Center
<b>K</b>	
K	Potassium
K	Kelvin
KCl	Potassium Chloride
kg	Kilogram
KI	Iodized Salt
km	Kilometer
KO <sub>2</sub>	Potassium Dioxide
Kr	Krypton
KREEP	Potassium (K), <u>R</u> are <u>E</u> arth <u>E</u> lements, Phosphorous (P).
KSC	Kennedy Space Center
kW	Kilowatt
<b>L</b>	
L	Liter
LC	The Liability Convention
LEM	Lunar Exploratory Module
LEO	Low Earth Orbit
LG	Luna Gaia
Li	Lithium
LiH	Lithium Hydride
LiOH	Lithium Hydroxide
LiHCO <sub>3</sub>	Lithium Bicarbonate
LRO	Lunar Reconnaissance Orbiter
LSAM	Lunar Surface Access Module
LuGaLiSuS	Luna Gaia Life Support System
<b>M</b>	
M <sub>2</sub> CO <sub>3</sub>	Carbonate Alkali Compound
M\$	Millions of Dollars
MA	The Moon Agreement
MALEO	Modular Assembly in Low Earth Orbit
MCP	Mechanical Counter-Pressure
MELiSSA	Micro-Ecological Life Support System Alternative
MEMS	Micro-Electro-Mechanical Systems
MeV	Mega-Electron-Volts
Mg	Magnesium
MgHCO <sub>3</sub>	Magnesium Bicarbonate
mg	Milligram
mL	Milliliter
mm	Millimeter
Mo <sub>2</sub>	Diatomic Molybdenum

MoH	Molybdenum Hydride
MOU	Memorandum of Understanding
MTCR	Missile Technology Control Regime
MW	Megawatt
mW	Milliwatt
<b>N</b>	
N	Nitrogen Element
N <sub>2</sub>	Diatomic Nitrogen
N <sub>2</sub> O	Nitrous Oxide
Na	Sodium
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection and Measurements
Ne	Neon
NH <sub>4</sub>	Ammonium
NH <sub>4</sub> <sup>+</sup>	Ammonium Ion
Ni	Nickel
NiCad	Nickel-Cadmium
NiMH	Nickel-Metal-Hydride
NiZn	Nickel-Zinc
NO <sub>2</sub>	Nitrogen Dioxide
NO <sub>3</sub> <sup>-</sup>	Nitrate Ion
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
<b>O</b>	
O	Oxygen
O <sub>2</sub>	Diatomic Oxygen
OST	The Outer Space Treaty (1967)
<b>P</b>	
P	Phosphorus
PAGEOS	Passive Geodetic Earth Orbiting Satellite
PCR	Polymerase Chain Reaction
PEL	Peak of Eternal Light
pH	Measure of acidity of Hydrogen ions
PNST	Prometheus Nuclear System Technology
pO <sub>2</sub>	Partial Pressure of Oxygen
ppm	Parts per Million
PPP	Public Private Partnership
PPS	Post-Processing System
<b>R</b>	
R&D	Research and Development
RC	The Registration Convention (1957)
Ref	Reference
RFP	Request for Proposal
REGLISSE	Review of European Ground Laboratories and Infrastructures
RO	Reverse Osmosis
<b>S</b>	
S	Sulphur
SAWD	Solid Amine Water Desorber
SCRS	Sabatier Carbon Dioxide Reduction System
SFWE	Static Feed Water Electrolysis
Si	Silicon
SiO <sub>2</sub>	Silicon Dioxide
SMES	Superconducting Magnetic Energy Storage

SPE	Solar Particle Events
SPWE	Solid Polymer Water Electrolysis
SSP	Summer Season Program
STeReO	Solar Terrestrial Relations Observatory
Sv	Sieverts
SW	Solar Wind
<b>T</b>	
Th	Thorium
Ti	Titanium
TiO <sub>2</sub>	Titanium Dioxide
TLI	Trans Lunar Injection
TM-COG	Tubular Monolithic Ceramic Oxygen Generator
TP	Team Project
TRL	Technology Readiness Level
<b>U</b>	
UK	United Kingdom
UN	United Nations
UN	Uranium Nitride
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNGA	United Nations General Assembly
UO <sub>2</sub>	Uranium Dioxide
US	United States
USA	United States of America
USDA	United States Department of Agriculture
USSR	Union of Soviet Socialist Republics
UTJ	Ultra Triple Junction
UV	Ultraviolet
<b>V</b>	
V	Volt
VPCAR	Vapor-Phase Catalytic Ammonia Removal
<b>W</b>	
W	Watt
WFRD	Wiped Film Rotating Disks
WHO	World Health Organization
<b>X</b>	
Xe	Xenon
<b>Z</b>	
Zn	Zinc

---

# Introduction and Summary

According to ancient mythology, *Luna* was the Roman Goddess of the Moon, and *Gaia* was the Greek Goddess of the Earth. Today, the term “Gaia” has evolved to mean “the living Earth”. Together, the two terms form the title of this report: *Luna Gaia* illustrating the concept of the outlined project: to bring life to the Moon through the next generation of human space exploration.

Luna Gaia: a closed loop habitat for the Moon seeks to achieve a realistic integration of systems (biological, psychological, ecological, political, social, economical, mechanical and operational), to support an ideal profile of an optimum 11 (maximum 12) member human crew on the lunar surface for a period of 18 - 36 months. For this to occur, we consider the necessary applications, infrastructure, technologies and philosophies intending to achieve a self-sustaining closed loop habitat model for human settlement on the Moon by 2030.

The Luna Gaia model capitalizes on innovation, current exploration and lessons learned from prior space exploration experience, existing technologies and intellectual/ cultural properties. The system we recommend for the Luna Gaia is unique and timely. Based on worldwide research of closed loop life support systems, this report integrates proven and innovative solutions to achieve a relatively independent and highly reliable system. The Luna Gaia system builds on the successes, exploits the possibilities and identifies the potential compatibility of components of the NASA JSC Breadboard (USA), MELiSSA (Europe), Bios-1, 2 & 3 (Soviet/Russia), and CEBAS (Germany) mission designs. This includes a symbiosis of bio-regenerative and physicochemical solutions to achieve oxygen, water, energy, food growth and waste processing.

The Luna Gaia concept *appeals* for an infrastructure that can build the instrumentation and protocols necessary to further geophysical data, position, navigation and timing, communication and information systems monitoring, and situational awareness capabilities for example. It is also able to detail risk mitigation strategies by describing technical solutions in relation to ethical and philosophical considerations and the wider implications for international law, policy and future interplanetary social governance. Furthermore, we identify the kinds of assumptions that are required to respond to the critical climate and optimize the necessary utilities and operations by aggressively seeking appropriate risk countermeasures, contingencies and redundancies for project advancement.

In addition to the Moon's potential as a testing bed for innovative technologies, by virtue of its proximity to and isolation from Earth's political and economic processes, the Moon may also provide a promising testing bed for innovative modes of governance, innovative forms of social organization and management structures, as well as innovative modes of production and consumption. The project also identifies the potential for international public private partnerships

models, future opportunities, high yielding investment returns and Earth-based applications making recommendations pertaining to the systems architecture, engineering processes, and the research, development, lobbying and orchestration of separate phased precursor missions to reach this goal.

It must be reiterated, that the modular, bio-regenerative network of systems particular to the Luna Gaia design architecture is ambitious but feasible. The initial timeline and investment is reasonable compared to the magnitude of long-term applications and projected returns to the global economy. The risks are apparent but the benefits are significant. The management principles are sound and the legal frameworks have been defined. More importantly, the project vision is consistent with the preservation of life and interplanetary environmental protection. Luna Gaia affirms our commitment to global participation in the extension of human presence on the Moon, and beyond...

## **1.1 Mission Statement**

*“To create a responsible framework for the establishment of a long-term lunar settlement, functioning as an efficient self-sustained closed loop system with potential Earth applications.”*

## **1.2 Concept of Operations**

As the most realistic existing plan for lunar exploration, NASA’s Exploration Systems Architecture Study (ESAS) provides a helpful guideline in defining a timeline for the execution of this mission (NASA, 2006b). The Luna Gaia team has used that timeline as a foundation for building an operations concept to bring the vision to reality.

To ensure the success and economic feasibility of the extended occupation of Luna Gaia, an infrastructure of Earth-based support will need to be established, predicated on the assumption that international participation will be a core element of the lunar habitat program. In fact, the architecture roadmap for Luna Gaia will utilize a combination of missions from various space agencies and commercial entities to explore potential locations, to build up the habitat, and to deliver the required provisions for re-supply.

The proposed Luna Gaia architecture roadmap can be divided into a preliminary research phase followed by four construction phases and finally an operational phase as seen in the Gantt chart in Figure 1.2-1. A corresponding budget for this roadmap is available in the Business section of this report. It is important to note, however, that the roadmap is predicated on beginning assembly with humans at a solar minimum to minimize their risk as will be discussed later, while the budget has some flexibility and thus doesn’t need to be tied as tightly to a specific year by year schedule.

Prior to the Luna Gaia project, extensive research and development will be required to enable all the necessary technologies to be suitably developed for the proposed four mission phases. These recommendations are included within this project proposal.

Preliminary Phase: In order to lay the ground work for Luna Gaia, a series of four pathway-finding robotic precursor missions are recommended to explore the potential base sites. These will be required to properly characterize the lunar environment at the chosen location, and to test the technology required to make this happen. These missions are critical to do the following:



- Examine the potential locations,
- Characterize the composition of the regolith for *in situ* resource utilization (ISRU),
- Examine the dust environment to address contamination concerns, and
- Examine the radiation environment to validate proposed shielding schemes.

These four missions will capitalize on the knowledge gained from the currently planned lunar reconnaissance missions such as NASA’s Lunar Reconnaissance Orbiter (LRO) mission planned for October 2008 and India’s Chandrayaan scientific spacecraft planned for September 2007. Additionally, China and Japan have planned lunar observation missions: Chang’e in 2008 and Selene in 2007, respectively. These missions involve investigation of terrain roughness, terrain mapping, radiation, temperature mapping of shadowed craters, identification of ISRU landing sites, and of deposits of near-surface water.

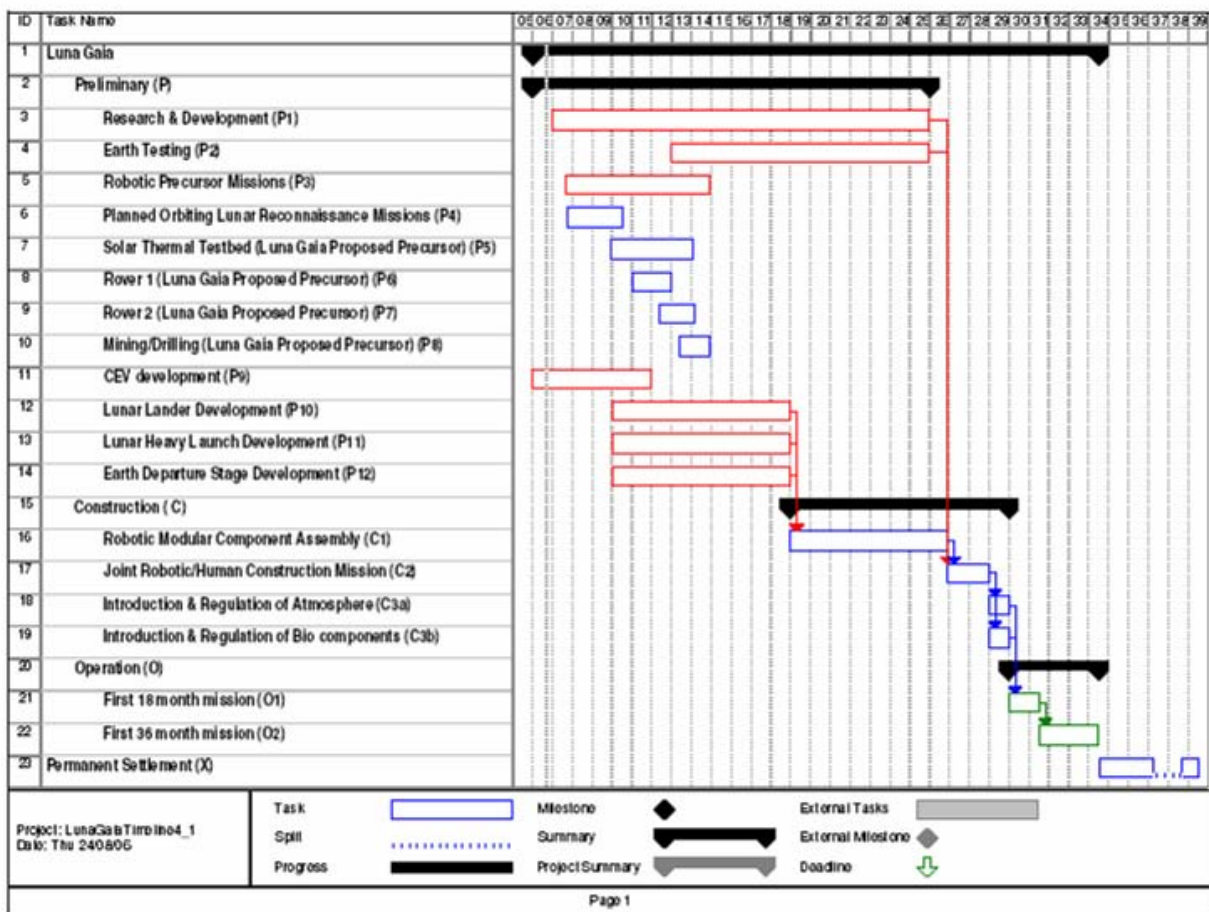


Figure 1.2-1 Luna Gaia Architecture Roadmap Timeline

The first of these missions is the demonstration of solar thermal power, and this should be completed about 5 years ahead of our construction phase. This timeframe should allow enough time to make the decision about continuing to use the baselined fission reactor or elect to use solar thermal instead. This mission is a small robotic mission with a deployment of a couple of small reflectors that focus light on the solar thermal generator unit. Since the demonstration is intended to properly characterize performance of the technology over several years, it can be utilized as a power source to drive instruments that characterize long-term aspects of the environment like radiation detectors and lunar dust

monitors. Particular attention would be paid to the effect of lunar dust on mirror refractive performance. Finally, this mission should include and monitor material samples and biological samples to characterize long-term effects of the lunar environment. The materials to be studied would include Carbon Fiber Reinforcement Plastic (CFRP) and Glass Fiber Reinforcement Plastic (GFRP) that are discussed in the Design Architecture section (Section 3.1) to characterize their performance in the lunar environment. Another material to be tested would be foam panels for the mounting of the photovoltaic cells. The foam will be transported in a highly compressed form and then expanded into a template to form panels. With duration of over 4 years to take advantage of the two rover missions to augment it, this mission is the longest of the proposed precursors.

Approximately 9 years before construction begins, but while the solar thermal demonstrator is still running, two identical missions much like the Mars Sojourner Rover would be sent one year apart to the same general area as the solar thermal demonstrator. These two missions give additional capability and also improve the chances of success of the objectives in case of a failure of one of the missions. These two missions provide data on dust scattering from the solar thermal instrument when they land in the neighborhood of the earlier mission. Much like Sojourner, these are rovers with cameras and spectrometers to refine the understanding of the composition of the regolith in the vicinity and to perform a geologic survey of the build site.

The fourth and final precursor mission is a technology demonstration of mining and drilling techniques to validate the ability to drill into the regolith for anchoring purposes for the habitat segments and various support equipment. Additionally, this is a chance to perform any ISRU technology demonstrations.

A space weather monitoring capability (such as that provided by the STeReO mission targeted launch in September 2006 and discussed within the Safety section of the Closed Loop Habitat portion of this report) is not integral to the Luna Gaia recommendations, but would be a key element in monitoring solar activity to provide advance warning of potential solar events for the lunar inhabitants. Such a capability is likely to already be driven by Earth-related concerns such as the safing of satellites and power systems due to solar events.

To analyze the operations concept of being able to deploy the Luna Gaia facilities, an overall mass budget was built compiling inputs from Habitat Architecture (Section 3.1), regenerative system components in the Closed Loop Life Support Systems (Section 3.2), and the power components (Section 2.3). This summarized data is presented in Figure 1.2-2. As discussed in Transportation (Section 2.4), the baselined cargo delivery vehicle is the Ares V. The major elements will be autonomously landed and deployed at the chosen location using robotic technology developed in the precursor missions. In forming the mass estimates of the lunar habitat, an analogy of the mass density of the United States Laboratory Destiny, of the International Space Station (ISS) (NASA, 2001), was used to calculate a relative mass for the volume described by the Luna Gaia architecture team. For comparison, another analogy was made using the mass density of the recently launched Bigelow Nautilus inflatable structure (Covault, 2004). Using the ISS analogy for total mass, 18 Ares V launches would be required while using the Bigelow Nautilus analogy would only require 10 Ares V launches. Thus an important recommendation of the Luna Gaia project analysis centers on a future investment in inflatable habitat technology to reduce costs of space-faring projects. At the bottom of Figure 1.2-2, the launches are broken into two deployment phases which are not to be confused with the construction phases. Instead the first of these phases is

deployment of equipment that will support an initial crew of four. The second phase enables the full Luna Gaia structure that supports a crew of twelve for the Operational Phase.

**Construction Phase:** To maintain a realistic budget profile, Luna Gaia should be built utilizing no more than two to three Ares vehicle launches in a fiscal year. In this seven year phase, there are two Ares V launches per year to pre-stage a majority of the Luna Gaia equipment prior to sending personnel.

In the first construction phase, deployment and robotic assembly of the Luna Gaia habitat begins. The intention of this phase is to launch, pre-stage, and assemble as much mass as possible without human intervention.

In the second construction phase, the steps for assembly requiring human support will occur at a solar minimum to minimize the radiation risk of the lunar expedition crew. The timing of the mission will coincide with solar minimum, with careful consideration and anticipation of periodic solar activity due to the strong magnetic field inversions before and after solar minimum. To allow for the required launch vehicle development as well as the technology development recommended in other areas of this report by the Luna Gaia team, the suggested opportunity at beginning of solar minimum is 2025. In this phase there are two Ares V launches per year, and an initial crew of four is supported by Ares I flights and re-supply flights every six months. The lunar inhabitants will nominally be launched using the Ares I in a Crew Exploration Vehicle as discussed in the Transportation section of this report. In Low Earth Orbit (LEO), they will join a LSAM, also launched by the Ares V, for the journey to the chosen location on the lunar surface. Ares I missions will be required to get lunar expedition crew members to the location to assist in the assembly and swap out crew members once every six months as recommended in the section below.

\*\*\*\*\* Note that launch are estimated on a Mass basis only since a detailed design was not performed. Design optimizations to maximize the density of the payload is assumed.

Power Systems	Mass (Kg)
Reactor	23000
Photovoltaic	1000
flywheel	3000
fuel cells	3000
<b>Total</b>	<b>30000</b>

Destiny ISS Lab	
Density (Kg/m <sup>3</sup> )*	159
Bigelow Nautilus module	
Mass (Kg) **	23000
Volume (m <sup>3</sup> )	330
Density (Kg/m <sup>3</sup> )	70

Baseline	
Legacy Structure (ISS based)	
Mass of Habitat (Kg)	343440
Mass of MELiSSA System (Kg)	5000
Powers Systems (Kg)	30000
<b>Total Mass (Kg)</b>	<b>378440</b>
Ares V lunar capability (Kg)	21000
<b>Ares V launches required</b>	<b>18</b>

Inflatable Habitat	
Mass of Habitat (Kg)	150545
Mass of MELiSSA System (Kg)	5000
Powers Systems (Kg)	37500
<b>Total Mass (Kg)</b>	<b>193045</b>
Ares V lunar capability	21000
Ares V launches required (theoretical)	9.2
Ares V launches required (actual)	10

Launching phases		
	First phase	Second Phase
Habitat Mass (Kg)	200340	143100
Power Systems (Kg)	30000	-
MELiSSA (Kg)	-	5000
Total mass (Kg)	230340	148100
Launches req'd	11	7

\* mass at launch + added payload racks  
 \*\* mass is fully loaded  
 These results are obtained under the assumptions that all power systems go in the first phase

Figure 1.2-2 Luna Gaia Mass Calculations

In the third construction phase the base becomes operational for long term stays for four crew members based upon physico-chemical environmental systems, and the lunar inhabitants in this phase begin to implement and maintain the regenerative systems that allow long-term sustainability.

Operational Phase: Permanent occupation of a fully operational Luna Gaia occurs with the full operational crew of eleven, capable of maximum operational capacity of twelve.

To be economically viable, the project attempts to achieve the highest percentage of recoverability of resources. Still, this approach leaves a gap in resources requiring re-supply of various commodities and the disposal of un-recovered assets without compromising the lunar environment. Thus, as discussed in the Transportation section, there is a limited amount of re-supply required for additional provisions and spare equipment for the Luna Gaia facility.

### *Lunar Inhabitant Rotation:*

Using the assumption of (at least) 2 launches a year for lunar inhabitants, and the aim of a mission length of initially 18 months, as a precursor to a 36 month duration, the lunar inhabitant rotation was decided to be as follows:

- Every 6 months (i.e. 1 of 2 launches a year) a group of 4 will travel to Luna Gaia to relieve 4 other inhabitants. Therefore, a total lunar inhabitant rotation of 8 persons per year will occur.
- With an operational maximum of 12 inhabitants for the micro-colony (as determined by its closed loop carrying capacity) and a 4 person turnover every 6 months, this allows for any 4 individuals to inhabit the base for an 18 month period from arrival to departure.
- When the micro-colony is ready to carry inhabitants for 36 month durations, the changeover rate can be cut down to 1 launch per year of 4 inhabitants, therefore providing a 3 year time span for each group.

Another approach to the 36 month mission goal may be to have only 4 persons on Luna Gaia serving the full term, and keep the other 8 inhabitants rotating on an 18 month rota, at 9 month intervals. This would allow for specialized missions for scientific, ISRU or other purposes and provide the added advantages of more frequent relief personal for the 'long term' lunar inhabitants. The arrival of new inhabitants will have major psychological effects, typically good ones. Further to this, in the case of a problem, the 'long term' inhabitants could return to Earth early in the place of the 'short term', while not drastically affecting the 'short term' group's mission duration (maybe lengthening their mission duration by 6-9 months). This approach of 4 'long term' inhabitants and 8 'short term' inhabitants may be a good option in the early operation of Luna Gaia when the psychological and physiological effects of long duration lunar settlement are not fully understood.

## **1.3 Overall Design Concept**

### **1.3.1 Architecture Design**

- The architectural design solutions focus on the coupling power for all regenerative processes of the network of closed loop life support systems (CLLSS).

- The concept for the human habitat itself uses physiological and psychological drivers to ensure optimal physical, mental and emotional human performance levels.
- The design solution extends openly to consider the type of utilization areas to facilitate the kinds of activities and applications that will be particular to both the mission design phases and the mission of operations.
- Looking to the future, the Luna Gaia design architecture easily facilitates the future expansion of human presence on the Moon, using modular systemization and construction so the lunar micro colony can grow indefinitely as humanity progresses

### **1.3.2 Closed loop life support systems (CLLSS)**

- Integrating the algae-oxygen-regenerator concept developed in Bios-3, concepts of bacteria-regeneration explored in MELiSSA with additional bio-regenerative processes including a new bacteria, fish and some physical filtration processes.
- Achieving an estimated 90-95% closed loop life support system with little dependency on re-supply and in-situ resource utilization (ISRU).

### **1.3.3 Health**

- Considering the physical well-being of the settlers living, and working for extended periods under extreme environment conditions to determine countermeasures from resistive exercise regimes to suppressing plasma volume loss.
- The challenges for personal and social well-being of the settlers are identified to make recommendations regarding lunar inhabitant; training, interface design, and workload.

### **1.3.4 Location**

- Various possible locations on the lunar surface are compared and a small crater of permanent darkness (<2 km in diameter) located in the Peary Crater region of the North Pole, and surrounded by peaks of eternal light (PELs) is identified as the site for Luna Gaia.

### **1.3.5 In-Situ Resource Utilization (ISRU)**

- SiO<sub>2</sub> to be used as a protective coating for reflective surfaces (heliostats).
- H<sub>2</sub> and O<sub>2</sub> extracted from lunar soil to be used as fuel for fuel cells.
- Except for initial population of the CLLSS, ISRU is only to be used only for energy storage (fuel cells) and to compensate for inefficiencies in the CLLSS.

### **1.3.6 Enabling Framework**

- Philosophical and ethical factors related to the Luna Gaia vision are identified to highlight the potential this project has for a renewed evaluation of future social governance and to identify the relevant international implications that may follow decision-making processes.
- Consideration of new and responsible means of inspiring the will, and confidence, which will be required to propel humanity, and its technology, towards the next frontier of lunar settlement are also discussed in relation to potential management structures.

### **1.3.7 Policy**

- This report intends to provide a roadmap to enable the success of the Luna Gaia mission by identifying critical policy areas that must be addressed to achieve this vision.
- Four key areas are identified for immediate consideration in this area: discussions pertaining to the establishment of a governing body; pathways for private industry; planetary protection and issues such as the use of Nuclear power in space are each highlighted .

### **1.3.8 Law**

- Identifying the current legal status and identifying the potential challenges for mission success.

### **1.3.9 Power**

- Consideration of the power system for Luna Gaia includes four separate systems approaches: nuclear fission or solar thermal, photovoltaics, flywheels, and fuel cells are highlighted.
- Fuel cells are also considered as solutions for power of surface transportation vehicles.



# Mission Planning Requirements

## 2.1 Requirements

After defining the mission statement, the team created a set of overarching requirements to be met during the design of the closed loop lunar habitat. These requirements are intentionally broad and meant to be used to ensure the program's scope and focus were consistent from beginning to completion. The list can be found in Table 2.1-1, along with a mention of which sections of the report address each specific requirement.

**Table 2.1-1 Program Requirements**

Requirements	Sections
The proposed design for a lunar habitat shall make every effort to use a fully closed loop life support system	3
The location for the Moon settlement shall be chosen to maximize <i>in situ</i> resource utilization (ISRU), use of terrain and exposure to sun	2
The proposed strategy for launching shall consider and make use of existing or near-term solutions from a variety of sources	2
The habitat shall be modular to increase redundancy, facilitate construction and expansion	3
The proposed concept shall be a stepping stone to permanent human presence in space in the form of colonies and further exploration of Mars and beyond	3,4
The proposed concept shall balance risk by using existing or near-term solutions as the baseline while recommending research on areas with a potential to improve feasibility and reduce cost, mass and schedule	2,3
The proposed concept shall include recommendations for establishing a policy legal framework to appropriately regulate all aspects of the project	5,6
The proposed concept shall have a realistic and responsible budget based on current assumptions	7
The habitat shall provide adequate protection for its inhabitants against radiation and contaminants such as lunar dust	3
The habitat shall be designed to maintain and strengthen the physical and psychological health of its occupants	3
The habitat shall be designed with a emphasis on identifying and developing technologies with applications on Earth to promote sustainability	8
The concept shall explore the ethical and philosophical considerations associated with establishing a responsible lunar settlement	4
The proposed concept shall explore the inner workings of private-public partnership (PPP) and International cooperation	7

## 2.2 Location

### 2.2.1 Location Considerations

The choice of a location for a lunar habitat depends on many factors, such as the available resources, temperature variation, availability of sunlight, environmental conditions (radiation, topology, surface composition, etc.), and the ability to view the Earth (both for communications and for psychological reasons). Accessibility for the delivery of materials from Earth may also be considered a deciding factor; however research shows that location does not have a significant impact on the amount of payload that can be delivered to the surface of the Moon (see section 2.4, Transportation).

### 2.2.2 Lunar Resources and Soil Composition

The data currently available regarding the composition of the lunar surface has been collected through the analysis of lunar samples (soil and rocks) returned from the Apollo (1969 – 1972) and Russian sample return missions as well as remote sensing data collected from more recent orbiting missions, such as Lunar Prospector (1989 – 1990), Clementine (1994), and Smart-1 (2006). The Galileo spacecraft also collected some data while passing by the Moon in 1990 & 1992.

The lunar surface consists chiefly of minerals containing aluminum (Al), calcium (Ca), iron (Fe), magnesium (Mg), oxygen (O), silicon (Si), and titanium (Ti). Figure 2.2-1 below shows the relative abundance of these elements on the lunar surface. There is hydrogen around 1% by mass, and the quantity is considerably higher in the polar regions. There is an ongoing debate as to whether this H at the poles may be in the water ice in the permanently shadowed regions (Rapp, 2006).

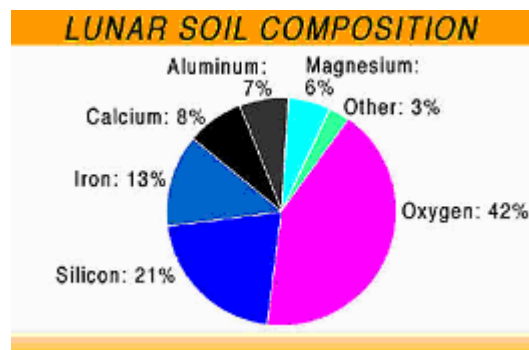


Figure 2.2-1 Lunar Soil Composition Composition (Averaged Over Entire Surface)

### 2.2.3 In Situ Resource Utilization

Lunar resources can provide many life supporting elements and construction materials for a lunar habitat, and can also be used as a source of power. A long-term presence on the Moon necessitates maximum utilization of these *in-situ* materials in order for the habitat to become as independent from Earth as possible, thus reducing the cost of re-supply and increasing long-term sustainability.

One material of particular significance is oxygen, which can be used to maintain a breathable atmosphere inside the lunar habitat, in fuel cells for the generation of power, and as a propellant for transportation systems using chemical propulsion.

Table 2.2-1 lists a number of candidate processes for the extraction of oxygen from lunar regolith.

**Table 2.2-1 Candidate Processes for Oxygen Production on the Moon**

Processes	References
Solid/Gas Interaction	
Ilmenite Reduction with Hydrogen	Gibson & Knudsen (1985) Chang (1959);
Ilmenite Reduction with C/CO	Shadman & Zhou (1988)
Ilmenite Reduction with Methane	Friedlander (1985)
Glass Reduction with Hydrogen	McKay et al. (1991)
Silicate/Oxide Melt	
Molten Silicate Electrolysis	Haskin (1985)
Fluxed Molten Silicate Electrolysis	Keller (1986)
Pyrolysis	
Vapor Pyrolysis	Steurer & Nerad (1983)
Ion Plasma Pyrolysis	Steurer & Nerad (1983)

Some of the many minerals found on the Moon can be reacted thermo-chemically with other gases (such as H<sub>2</sub>) to produce oxygen, Table 2.2-1 (Lewis J. S., 1993) Several of these processes use the mineral ilmenite (FeTiO<sub>3</sub>) to reduce the FeO portion and leave a product of TiO<sub>2</sub> + Fe, which releases oxygen. The oxygen then combines with the input H<sub>2</sub> to form water, which can be used directly in the CLLSS (see Section 3.2, CLLSS) or be broken down further through electrolysis to form O<sub>2</sub> and H<sub>2</sub>. This is a proven industrial process that was included in the patent application of Chang (Lewis J. S., 1993); however, it is important to note that it is not always easy to obtain ilmenite from the mare lavas and lava-derived soils found on the Moon, since the ilmenite is usually combined with other minerals.

Metals such as iron are by-products of all schemes for oxygen production on the Moon. As iron is as a highly available resource (titanium is found in much lower concentrations), it could be used for making infrastructure/buildings, tools, machinery and electrical distribution systems. The extraction of iron metal can be obtained in unlimited quantities by reductive extraction from mare basalt or agglutinates which contain much of the regolith's iron. Our site location is amongst meteoritic impact craters, which could mean an increase in Fe availability. Meteorites of more than 10<sup>6</sup> tons have been found on Earth, and such a find on the Moon could be a valuable source of rich-Fe fragments that could be molten in various shapes.

The highlands found in the older areas of the lunar surface are usually covered by more regolith, to a maximum depth of 15 meters. The composition of the sand lying on top is directly derived from the local anorthositic rock which is made of feldspar, which is an aluminum-rich rock-forming mineral. By a process know as fluorination, the aluminum and oxygen of the Al-rich oxides are extracted from the regolith (Lewis J. S., 1993). Highland-derived regolith contains an abundance of calcium and sodium (Na), which could be used for sustaining plant growth. For the same reason, soils derived from rocks such as those in the maria – large, dark basaltic plains found on the lunar surface – are an excellent source of magnesium, which is utilized in fertilizers. KREEP-rock soils would be an

excellent *in situ* source of potassium (K) and phosphorus (P) if found near the site (where KREEP refers to the chemical symbol for potassium (K), Rare Earth Elements, and the chemical symbol for phosphorous (P)).

The typical amount of silicon in lunar soil is between 10-20%. Heating the regolith to about 700°C through amplified solar reflection will liberate most of the volatiles including hydrogen (H) which could be recovered and stored. Heating above 1050°C will melt most of the remaining elements to form glass and fiberglass. The regolith can generally be gathered on all types of lunar terrains; therefore it is the most accessible non site-specific resource for surface construction such as landing pads, walls and energetic radiation shielding, (Rapp, 2006) through the use of regolith-based construction materials (such as ceramics or cement). Although developments have been made in testing extraction processes with different gases, energy requirements as well as *in situ* concentrations of minerals of interest will have to be assessed at the chosen location. Exploration throughout the mission may reveal new and unexpected deposits of potentially useful resources.

### 2.2.4 Lunar Regions

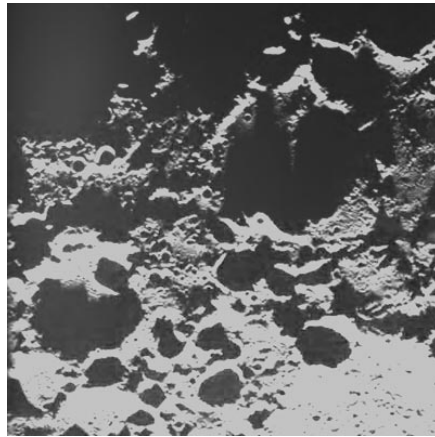
Taking the various considerations into account (see Section 2.2.1, Location Considerations), the practicability of both polar and non-polar locations for a lunar habitat was considered. Table 2.2-2 summarizes the general advantages and disadvantages of these regions.

**Table 2.2-2 Comparison of Lunar Regions**

Region	Advantages	Disadvantages
<b>Polar</b>	<ul style="list-style-type: none"> <li>• Constant line of communication with Earth</li> <li>• Constant availability of sunlight on PEL (although the angle of incidence varies)</li> <li>• Simultaneous access to both light and dark areas of the lunar surface</li> <li>• Access to areas of permanent darkness</li> <li>• Increased concentrations of hydrogen</li> <li>• Possible availability of water</li> </ul>	<ul style="list-style-type: none"> <li>• Certain lunar resources are less well understood (e.g. Ti, Mg, Fe, Th, K)</li> </ul>
<b>Non-polar, Earth side</b>	<ul style="list-style-type: none"> <li>• Constant line of communication with Earth</li> <li>• Lunar resources are found in greater abundance (e.g. Ti, Mg, Fe, Th, K)</li> </ul>	<ul style="list-style-type: none"> <li>• High degree of thermal variation (increase in structure complexity)</li> <li>• Solar power is less viable as the primary source of energy due to long periods of darkness</li> </ul>
<b>Non-polar, far side</b>	<ul style="list-style-type: none"> <li>• Optimal location for deep space observation in radio frequencies</li> </ul>	<ul style="list-style-type: none"> <li>• High degree of thermal variation (increase in structure complexity)</li> <li>• Solar power is less viable as the primary source of energy due to long periods of darkness</li> <li>• Communication with the Earth requires relays (i.e. communications satellites in lunar orbit)</li> </ul>

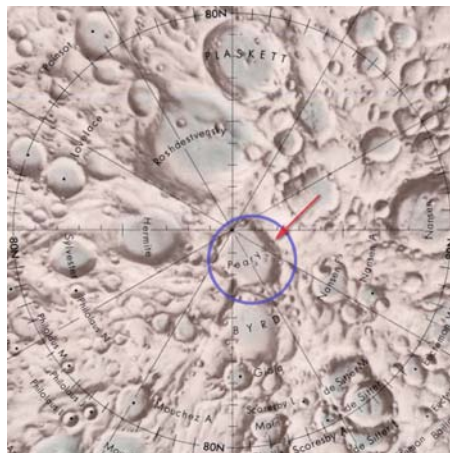
### Recommendations

The North Polar Region is our recommended location for a lunar habitat, specifically the area surrounding the Peary Crater. In general, a polar location is preferable due to the relative lack of thermal variation throughout the lunar day, and the availability of Peaks of Eternal Light (PELs). When the North and South Poles are compared through composite images of light exposure, the North Pole shows a greater area of illumination, as illustrated by Figure 2.2.-2 (Wingate). These composite images produced by the Clementine spacecraft show the addition of alternate polar orbit images over the course of one lunar day (one Earth month). Figure 2.2-2 shows an image depicting illumination of North Pole close to the winter solstice. This area is identified as having Peaks of Eternal Light.



**Figure 2.2-2 250 Km-Wide Image of Lunar North Pole Taken from SMART-1**

The area surrounding the Peary Crater not only contains a high concentration of hydrogen, but also provides access to both a high ridgeline (containing numerous PELs) and a number of craters of permanent darkness. In order to support the proposed design architecture (Section 3.1, Design Architecture), a small crater of permanent darkness (< 2 km in diameter) must be selected, with a number of PELs around the rim. Based on the current level of information, Figure 2.2-3 shows one possible candidate location (indicated by the arrow) for such a habitat, although more reconnaissance will be required before a final location can be selected. See Section 1.2 for a description of the precursor missions planned.



**Figure 2.2-3 Recommended Habitat Location (Regional map)**

## 2.3 Power

The main objectives of the power system are to provide sufficient levels of power for operation of the lunar habitat while maximizing long-term sustainability, providing multiple levels of redundancy, and minimizing overall maintenance, replacement, and re-supply from Earth. It is also desirable to have a power system from which the power output can be scaled to meet the dynamic needs of the habitat, such as short-term demands for high levels of power, and increasing power demand as the habitat grows in size.

### 2.3.1 Power budget

#### *Nominal Operation of Habitat*

The Luna Gaia power budget is based on power usage data provided by the ISS. This data was scaled according to both crew size and habitat volume. The power estimates for the CLLSS and ISRU were based on the specific design of the lunar habitat.

During nominal operation, all systems are provided with power. The CLLSS is the primary power consumer, requiring approximately 280 kW of power to support a 12-person crew. For information on systems requiring power in the CLLSS see Chapter 3. The ISS allocated a power budget of 46 kW for science projects. In comparison the power allocated to science projects in Luna Gaia will take up to 54 kW, which should provide enough power to do experiments, observations etc. Hydrogen and oxygen extraction from the lunar soil to make fuel is another significant power user (oxygen generation requires 3.5 kW-yr/ton). An allocation of 135 kW for ISRU is sufficient to generate fuel not only as a backup supply of power but also for use in chemical propulsion systems (i.e. visiting spacecraft) and for lunar surface transportation vehicles (Section, 2.4.3 Other Transportation Needs). Using less than this allocation of power has no detrimental impact on the operations of the habitat (other than reducing the available contingency reserves of power), as long as enough fuel is still being produced to support lunar surface transportation needs. The 43 kW allocated for the thermal control subsystem should be more than enough power to provide thermal regulation, such as for heat removal from the CLLSS greenhouse. This number is partially based on ISS estimates and also on figures from large scale cooling projects (i.e. 36kW are required to provide cooling to a medium-sized office building). The requirements for the other subsystems are estimated based on data provided from previous missions. A margin of 10% is added for safety, Table 2.3-1.

**Table 2.3-1 Nominal Power Usage**

Subsystem	Percentage of total power (%)	Nominal operation power budget (kW)
<b>CLLSS</b>	52	280
<b>Science</b>	10	54
<b>Propulsion (rover fuel)/ISRU</b>	25	135
<b>Communications</b>	1	5
<b>Command and Data Handling</b>	4	22
<b>Thermal</b>	8	43
<b>Total</b>	<b>100</b>	<b>539</b>
<b>Total with power losses of 10%</b>		<b>592</b>
<b>Total with margin of 10%</b>		<b>646</b>



*Minimal Power Requirements*

In case of an emergency some systems will be shut down to save power for more essential systems. In this case, the power is provided by a backup system of solar photovoltaic arrays. To sustain elementary functions, the CLLSS needs approximately 20% of its nominal power. Fuel extraction, communications and data handling need only part of their nominal power requirement, and all science experiments can be stopped. Thermal control however needs to be fully operational. The total amount of backup power, 146 kW, needs to be provided by the solar array backup system, Table 2.3-2. Therefore, there is no time limit for running in emergency mode (as long as solar arrays are functional).

**Table 2.3-2 Minimum Power Usage**

Subsystem	Percentage of nominal operation power (%)	Min power (kW)
<b>CLLSS*</b>	20	56
<b>Science</b>	0	0
<b>Propulsion (rover fuel)/ISRU</b>	5	7
<b>Communications</b>	50	3
<b>Command and Data Handling</b>	60	13
<b>Thermal</b>	100	43
<b>Total</b>		<b>122</b>
<b>Total with power losses of 10%</b>		<b>134</b>
<b>Total with margin of 10%</b>		<b>146</b>

\*Not fully functional at onset of construction phase

*Build-up Phase Requirements*

During the establishment of the infrastructure, not all systems will be operational. Initially, all resources are transported from Earth to support the closed loop life support system. Science projects will run at a reduced power capacity since they are not yet fully operational. Since material will have to be transported the lunar rovers will expend more fuel, and communications with the robots must be fully operational. Other systems will not be running at full capacity, since they will not yet be completed. For estimated power usage during construction phase, see Table 2.3-3.

**Table 2.3-3 Estimated Power Usage During Build-Up Phase**

Subsystem	Percentage of nominal operation power (%)	Power during build-up (kW)
<b>CLLSS</b>	10	28
<b>Science</b>	30	16
<b>Propulsion (rover fuel)/ISRU</b>	200	269
<b>Communications</b>	100	5
<b>Command and Data Handling</b>	40	9
<b>Thermal</b>	50	22
<b>Total</b>		<b>349</b>
<b>Total with power losses of 10%</b>		<b>384</b>
<b>Total with margin of 10%</b>		<b>419</b>

### 2.3.2 Power Generation Options

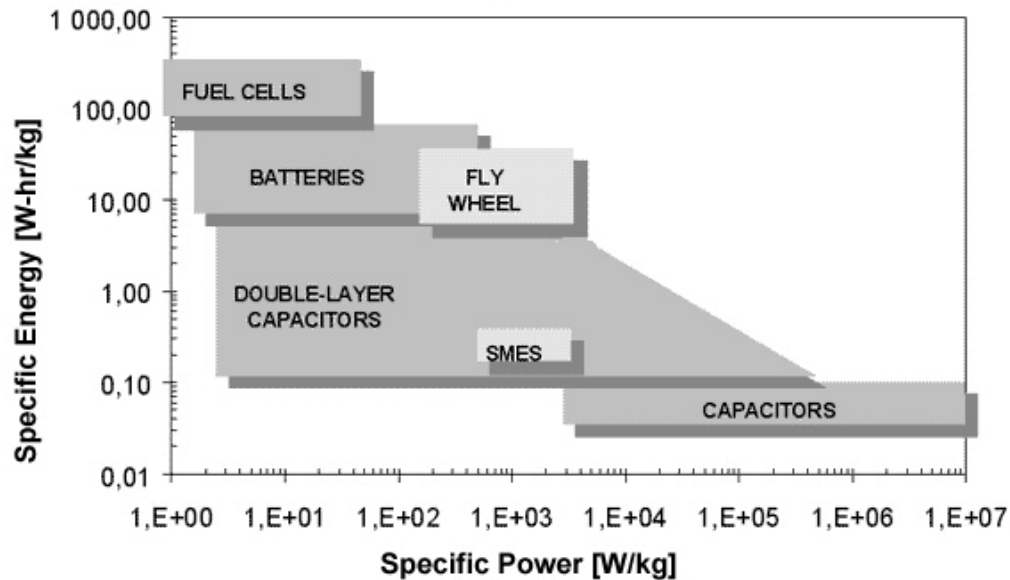
There are a number of power generation options available for the lunar habitat. The following table summarizes the general advantages and disadvantages of each method of power generation as it applies to the lunar environment.

**Table 2.3-4 Comparison of Power Generation Options**

Method	Advantages	Disadvantages
<b>Photovoltaic</b>	<ul style="list-style-type: none"> <li>• Proven technology</li> <li>• Minimal infrastructure required</li> <li>• Scalable</li> <li>• Reliable</li> <li>• Lower efficiency photovoltaics can be manufactured using lunar resources</li> </ul>	<ul style="list-style-type: none"> <li>• Large area required for high power generation</li> <li>• Requires rotating structure(s) for tracking the Sun</li> <li>• Power level degrades over time</li> <li>• Requires periodic replacement</li> <li>• Affected by environmental conditions</li> </ul>
<b>Solar Thermal</b>	<ul style="list-style-type: none"> <li>• Proven technology</li> <li>• Scalable</li> <li>• Inexpensive</li> <li>• May also be used as a source of heat</li> </ul>	<ul style="list-style-type: none"> <li>• Large area required for high power generation</li> <li>• Requires rotating structure(s) for tracking the Sun</li> <li>• Requires complex infrastructure (complicates initial construction)</li> <li>• Affected by environmental conditions</li> </ul>
<b>Nuclear Fission</b>	<ul style="list-style-type: none"> <li>• Proven technology</li> <li>• High power density</li> <li>• May also be used as a source of heat</li> </ul>	<ul style="list-style-type: none"> <li>• Political and social issues associated with use in space</li> <li>• Limited lifespan</li> <li>• Requires complex infrastructure (complicates initial construction)</li> <li>• Large system required for sufficient heat dissipation</li> <li>• Requires radiation protection for crew</li> </ul>
<b>Microwave Energy Transfer</b>	<ul style="list-style-type: none"> <li>• Scalable</li> <li>• Capable of high power</li> </ul>	<ul style="list-style-type: none"> <li>• Not proven</li> <li>• Inefficient</li> <li>• Requires Earth-based infrastructure (not lunar self-sufficient)</li> <li>• Creates environmental risk for objects passing through line of sight (i.e., satellites, airplanes)</li> </ul>
<b>Nuclear Fusion</b>	<ul style="list-style-type: none"> <li>• High power density</li> </ul>	<ul style="list-style-type: none"> <li>• Not proven</li> <li>• Requires steady input of fuel</li> <li>• Requires complicated infrastructure</li> </ul>

### Power Storage and Regulation

Power storage and regulation options must be evaluated based on two different characteristics: energy density, and power density. Figure 2.3-1 compares the different power storage options based on these characteristics.



**Figure 2.3-1 Comparison of Different Methods for Energy Storage**

### Recommendations

As a result, the recommended power system for the lunar habitat consists of four separate power systems, as illustrated in Figure 2.3-2 and described below:

- Primary Power Generation: Baseline: nuclear fission; Alternative: solar thermal (contingent on further research: limited deployment initially, not relied on for critical systems)
- Secondary Power Generation: Photovoltaic
- Primary Power Storage (& Regulation): Flywheels
- Secondary Power Storage: Fuel cells

During normal operation, power will be supplied by either a nuclear fission reactor). In the event of a failure, photovoltaic cells will be used as a backup to provide the required power for life support and habitat sustainability. The use of photovoltaic cells as the primary source of power was discounted, since they degrade through normal use and require periodic replacement. Solar thermal technology is a promising option which will be investigated through precursor missions. If successful, it is the leading candidate to replace nuclear fission as the primary source of power.

For power storage, flywheels will be the primary method of storage. They will also be used to regulate the power output of the power generation systems to ensure the quality of the power supply. When the flywheels start to approach their maximum storage limits, the excess energy generated can be drawn off and used to extract H<sub>2</sub> and O<sub>2</sub> from the lunar soil, which will then be used as redundant power storage (fuel for fuel cells). The use of batteries for power storage was discounted, since they also degrade through normal use and require periodic replacement.

Since each of these systems is able to operate independently, multiple systems can be used simultaneously for relatively short durations (up to several days) in order

to meet peak power demands of up to twice the nominal power load (~1.3 MW). Each of these systems is discussed in greater detail in the following sections.

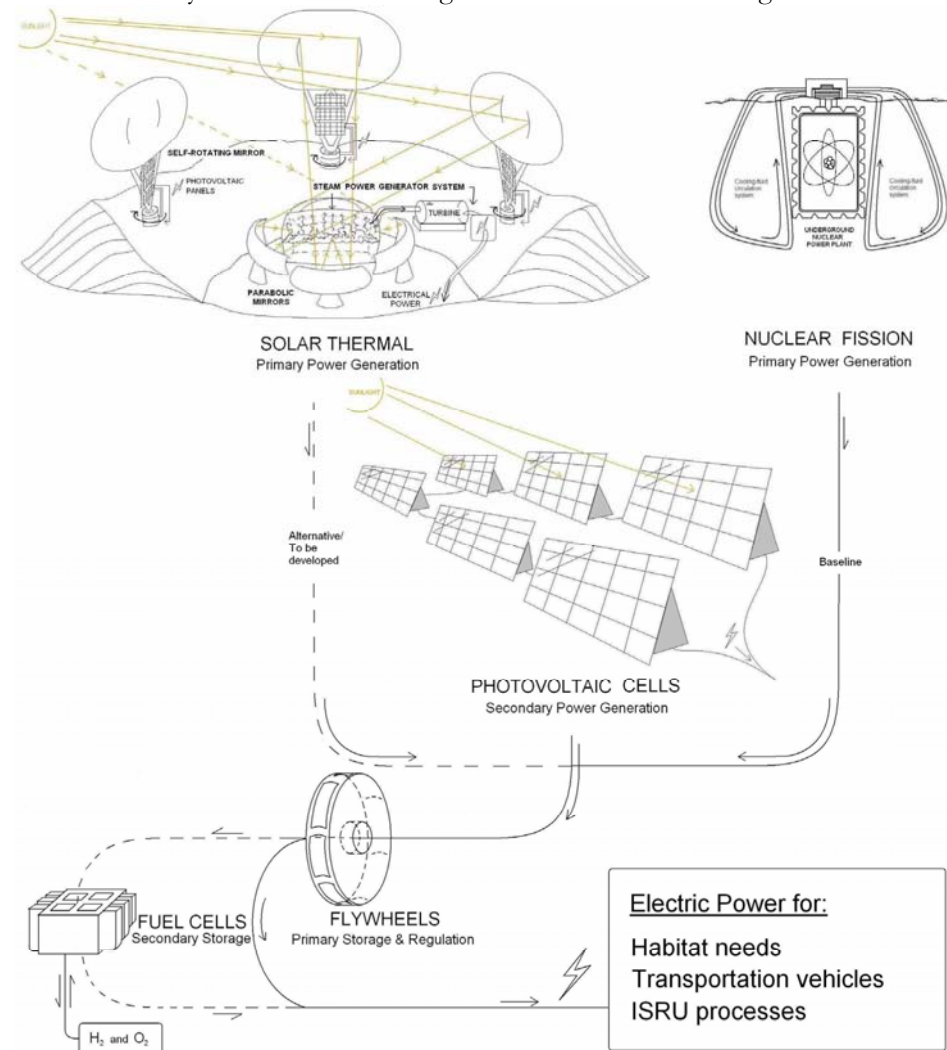


Figure 2.3-2 Lunar Habitat Power System

### 2.3.3 Primary Power Generation

Primary power generation needs can be met by either nuclear fission or solar thermal power generation technology, both of which are proven methods of large scale power generation.

Given the current level of understanding, nuclear fission technology serves as the baseline for the primary power generation needs of the lunar habitat; however, should preliminary testing of solar thermal power generation (see Section 1.2, Concept of Operations) prove it to be a viable source of energy, solar thermal power would become the recommendation as the primary source of power generation.

#### *Nuclear Fission Power in Space*

One of the most important considerations in mission design including those that use fission reactor power systems is safety during pre-launch, launch, mission operation and post-operation phases. Extensive testing and analysis is required to ensure the safety of the public and the environment. Under existing NASA guidelines a space fission system will only be turned on (i.e. made ‘critical’) once

the system has reached its startup orbit or interplanetary trajectory (Energy, Feb-03). In the case of a lunar Fission Surface Power System (FSPS), the reactor would most likely not be made critical until it is secure in its permanent location within appropriate shielding. From initialization of the reactor the waste that will be produced must be taken into account. The reactor must either remain at its predetermined location indefinitely, in order to allow the radioactivity produced during operation to naturally decay away, or have a nearby radiation disposal site prepared. To reduce the possibility of exposure to radioactive or toxic substances and to assure security and protection of fissionable materials, a hierarchy of safety goals is used (called Integrated Safety Management). This includes objectives, criteria, requirements and specifications regarding a specific system. In mission and system design typical requirements include: 1) reliable operation without continual actions from ground control, 2) the ability to keep the reactor subcritical prior to startup and during various accident scenarios, 3) the ability to remove operational and decay heat during both normal and off-normal operating conditions, and 4) the ability to reliably perform all necessary control and safety functions.

The presence of a FSPS may introduce new complications regarding assembly, test and launch processes. The use of high temperature materials (>1200 K) such as refractory alloys which are not used in commercial nuclear power plants or research reactors may be a concern and the development of specialized nuclear fuels may require a long time period. The reactor systems must be able to withstand the vibration and acceleration forces associated with launch and they must also be designed to mitigate the effects of severe accidents such as launch-pad explosions or events such as re-entry into Earth's atmosphere (Science).

### *A Potential Fission Reactor*

Current theoretical FSPS are sized from 50 to 200 kW of electrical power, which is not enough to support a closed loop infrastructure such as the one proposed in this document. A number of present day reactors may be required to meet the power demand of the system. The solution to this problem may be found in advanced reactors. These proposed advanced reactors are to be built entirely from carbon-based materials. The heat transfer medium between the reactor and power generation equipment and/or heat rejection systems could consist of salts (liquid or gas) or possibly lithium, to create reactor systems with very high power-to-mass ratios (Forsberg et al., April 15th 2005). The new reactors could have peak operating temperatures between 1800 and 2300 K with efficiencies twice that of other concepts. There are currently no other classes of materials that can operate at such high temperatures and have very low mass, therefore most of the components of such a reactor must be built from carbon-based materials (such as carbon-carbon composites). Significant research is necessary to demonstrate feasibility and a major long-term development program would be required to build such power systems (Forsberg et al., April 15th 2005). Carbon-carbon composites have the potential to dramatically improve performance.

### *Solar Thermal Power*

Nuclear fission is the baseline for primary power generation. However, solar thermal power generation provides the best balance of initial investment, system scalability, and long-term sustainability. Its greatest current drawback is the lack of technological maturity for use in the lunar environment. A precursor mission (see Section 1.2) dedicated to accelerating its development is planned. For the lunar habitat, a system would be set up based on the solar furnace design of a solar thermal system. A number of heliostats (flat, circular mirrors) would be set up (around the rim of the crater in which the habitat is located) on the PELs to

direct the light into the crater onto a fixed parabolic concentrating mirror, which would then focus the light into a heat capacitance fluid -- in this case, water. Since the focused sunlight does not introduce harmful radiation into the resulting steam, the water from the CLLSS can be used in the power generation cycle, providing an even greater level of sterilization to the water recycling system. The steam produced would then be converted into electrical energy via a steam turbine. A set of four equally spaced fixed parabolic concentrating mirrors around the boiler will provide for the focusing of incident sunlight from all directions. An illustration of this system is shown in Figure 2.3-2.

The heliostats around the crater rim would be actuated in order to track the sun. These heliostats would be made of reflective UV-treated polymer material, and coated with a SiO<sub>2</sub> protective coating that can be added on-site, using SiO<sub>2</sub> from the lunar soil. The SiO<sub>2</sub> film is applied to the reflective surface using Ion-Beam-Assisted Deposition (IBAD) (Swisher, 2005). Certain polymer membranes are currently able to achieve specular reflectances of around 95%. With a minimal amount of further research into this technology, a specialized membrane can be developed even further to improve specular reflectance, and to reduce the detrimental impacts of the lunar environment (such as surface contamination from lunar dust) (Kennedy, 2006). Another advantage of polymer membranes is that they can be rolled up for transport to the Moon, and then deployed by simply unrolling the pre-fabricated membrane onto the mirror actuation structure. Replacement of damaged reflectors can also be achieved through the same process, after the damaged membrane has been removed. Reflective polymers can be enhanced to prevent degradation of the reflective properties in the presence of UV radiation (Kennedy, 2006). As a result, the solar thermal power generation system based on reflective polymer technology has a long lifespan with minimal required maintenance.

To preserve the shape of the reflective surface, it is recommended to mount the polymer membrane on a solid surface made from a foam-based material. The foam can be transported from the Earth in a highly compressed form to minimize launch volume, and can be expanded into a panel template and allowed to cure into a solid state. Once fully cured, the completed panel can be removed from the template, and the process can be repeated until all of the necessary panel area has been formed. By mounting the polymer membranes to lightweight foam panels, the shape of the reflective surface can be maintained while minimizing the amount of mass requiring actuation (to maintain proper geometry to the incident sunlight). A precursor mission is required to prove the viability of foam panel creation in the lunar environment. Section 1.2 discusses the precursor missions in greater detail.

One distinct advantage of the solar thermal system is the scalability of the total power capacity. As the power needs of the habitat grow over time, the solar thermal system can be expanded by supplementing the existing system with additional heliostats around the crater rim. The only limiting factor to the maximum amount of power that can be generated using solar thermal energy is the availability of new locations on which to place additional heliostats (which must be located on a PEL). Similarly, the system can slowly be scaled up over time during the construction phases of the mission (See Section 1.2 Concept of Operation) to continually grow with the increasing power needs of the partially constructed habitat. Another advantage is many of the parts can be constructed from the lunar resources relatively easily compared with the fission reactor.

In order to supply the nominal power demand of 646 kW a series of heliostats totaling 8808.5 m<sup>2</sup> will need to be set up on the PELs. This area was determined using the following factors (Kennedy, 2006) (Paul W. Todd, 2006):

- Incident solar energy density on the lunar surface: 1368 W/m<sup>2</sup>
- Percentage of solar energy (frequencies) that is useful for heating water: 60%
- Minimum incidence angle to the heliostat: 45°
- Reflective efficiencies of heliostats and concentrating mirrors: 90%
- Reflection loss from heliostat to concentrating mirror: 20%
- Overall conversion efficiency from thermal to electrical energy: 30%
- Percentage of heliostats that can be used at one time (due to geometric limitations): 65%

The required area can be provided through the use of 12 circular heliostats, each of which is 30.6 meters in diameter. Alternatively (for greater efficiency), a system of 64 circular heliostats can be used, each of which would be 13.3 meters in diameter.

The power for each actuating mirror would be provided by a single panel of silicon-based photovoltaic cells. This allows for each actuation mechanism to have an independent supply of power, eliminating the need for a large power infrastructure. The silicon-based photovoltaic cells can be replaced using lunar resources.

The same software used in terrestrial systems to track the sun and properly focus the incident sunlight can be directly used for the lunar habitat, with little to no modifications. This decreases the overall development cost of the solar thermal system.

It is also important to note that the heliostats deployed around the crater rim would be identical to the mirrors required to reflect sunlight into the habitat greenhouse. As a result, overall system cost can be further reduced due to the availability of components that have already been developed for another subsystem. The large number of heliostats also adds to the overall redundancy of both the power generation system and the CLLSS, since any of the heliostats can be used to support either subsystem.

### **2.3.4 Secondary Power Generation**

For redundancy, photovoltaic cells will be used as a backup to the primary power system. Photovoltaic cells will also be used to provide power during the initial phases of construction, while the primary power generation system is still being installed and initialized. Silicon-based photovoltaic cells can be manufactured using lunar resources; however, it is recommended to use gallium arsenide photovoltaic cells from Earth, since they operate at a much higher efficiency than the silicon-based cells. A comparison of the 2 options (gallium arsenide versus silicon) is shown in Table 2.3-5.

In order to provide a solid surface on which to mount the photovoltaic cells (solar panels), the recommendation is to use a foam-based material (identical to that proposed for the heliostats used in solar thermal power generation. Due to the reduced gravity, a foam panel on the Moon (compared to on Earth) can more easily support the weight of mounted photovoltaic cells (Foam), and by mounting the photovoltaic cells to lightweight foam panels the mass requiring actuation can be minimized.

The photovoltaic power generation system will be sized to only supply the minimum level of power required for short-term habitat sustainability, 146 kW. In order to provide this level of power, 381.2 m<sup>2</sup> of gallium arsenide photovoltaic cells will be required. (Panels)

**Table 2.3-5 Comparison of Photovoltaic Options**

<u>Cell Type</u>	<u>Weight</u> ( <sup>mgm</sup> / <sup>cm<sup>2</sup></sup> )	<u>Power</u> <u>Capacity</u> ( <sup>mW</sup> / <sup>cm<sup>2</sup></sup> )	<u>Power /</u> <u>Weight</u> <u>Ratio</u>	<u>Overall</u> <u>Efficiency</u> (%)
Silicon K4710	38.5	16.6	0.43	12.3
Silicon K4702	38.5	18.0	0.47	13.3
Silicon K6700B	54.2	18.5	0.34	13.7
Silicon K6700B Wrapthru	38.5	19.2	0.50	14.2
GaAs/Ge Single Junction	80	25.7	0.32	19.0
GaInP <sub>2</sub> /GaAs/Ge	84	29.5	0.35	21.8
GaInP <sub>2</sub> /GaAs/Ge Triple Junction	84	33.9	0.40	25.1
Improved Triple Junction (ITJ)	84	36.3	0.43	26.8
Ultra Triple Junction (UTJ)	84	38.3	0.46	28.3

### 2.3.5 Primary Power Storage & Regulation

For power regulation and primary storage, flywheels are the recommended solution. Flywheels are made to operate in a vacuum environment that is not required to be thermally controlled. Lightweight carbon flywheels are individually able to store reasonable amounts of energy (around 80 W-hr/kg) (MPower).

In order to allow the occupants of the lunar habitat sufficient time to switch to a redundant power source (either the photovoltaic panels or the fuel cells) in the event of a failure, the flywheel system is sized to provide the minimum level of power (146 kW) for up to 1 hour. This results in a system containing 1825 kg of flywheels (based on an average specific energy of 80 W-hr/kg), which can provide a total energy output of 146 kW-hr.

The flywheels also serve the function of regulating the flow of power throughout the lunar habitat, automatically compensating for fluctuations in the available power. The flywheels also automatically store any excess power that is generated by the power generation systems.

### 2.3.6 Secondary Power Storage

For redundancy, fuel cells will be used as a secondary method of power storage. Whenever the flywheels begin to approach their maximum storage capacity, some of the energy from the flywheels will be consumed to extract H<sub>2</sub> and O<sub>2</sub> from the lunar soil.

The fuel cell system must be sized to provide for the nominal power demand of 646. This results in a system containing 2307 kg of fuel cells (based on an average specific power of 280 W/kg).

The 135 kW allocated for ISRU allows for the extraction of 39 tons of oxygen per year from the lunar soil, which is enough fuel to provide continuous nominal



power levels (646 kW) to the lunar habitat for 14 days. Due to the cold temperature available in craters of eternal darkness (33 K), the oxygen can be stored in liquid form. It may also be possible to store the oxygen in solid form, since oxygen has a freezing point of 54.75 K. Solid oxygen has a density of 1.42 g/cm<sup>3</sup> (resulting in a volume of 0.704 m<sup>3</sup>/ton) (Hörl, 1961), while liquid oxygen has a density of 1.14 g/cm<sup>3</sup> (resulting in a volume of 0.877 m<sup>3</sup>/ton) (Wade, 1997 - 2006). In either case, the storage requirements for the oxygen are only 27.5 m<sup>3</sup>/year in solid form and 34.2 m<sup>3</sup>/year in liquid form. Storage of the H<sub>2</sub> and O<sub>2</sub> fuels can be done, in part, using the fuel tanks that are left behind from each LSAM descent module. For additional storage, inflatable containers can be supplied from Earth, which will be lightweight and able to be compressed to a small volume for transport to the lunar habitat.

## 2.4 Transportation

### 2.4.1 Earth to Moon

For lunar habitat construction, transportation systems are required to carry the crew, equipment and materials to the lunar surface. Various factors need to be considered in the design stage of transportation systems including mission planning, mission duration and other mission requirements. However, of the variables to consider in building the lunar habitat, logistics will have the greatest impact on overall mission planning.

In our launch vehicle analysis, NASA's Ares I and Ares V (NASA, 2006a) were chosen as capable launchers not because they are existing vehicles but because they are near-term launch vehicles that use existing technologies. Additionally, the U.S. has the most ambitious lunar exploration plan and funding profile to be able to carry launch vehicle development to fruition. Therefore we will choose these vehicles as the primary logistical transportation vehicle for crew and cargo. Table 2.4-1 shows the payload performance comparisons and estimated capability for lunar payload delivery for Ares I and V next to Apollo's Saturn V for reference (Smithsonian). Cost estimations were derived for these vehicles based on an evolutionary estimate from existing launch vehicles such as Shuttle, Atlas V, and Delta IV (Tech, 2001) (24-Mar-06) using \$2500/kg for the simpler Ares I and \$3500/kg for Ares V.

**Table 2.4-1 Performance Comparisons of Launch Vehicles**

	Ares I (Crew Launch Vehicle)	Ares V (Cargo Launch Vehicle)	Saturn V (for reference only)
Payload mass [t] (to LEO)	25	130	118
Payload mass [t] (to TLI)	12	65	47
Payload mass [t] (est. to Moon)	5	22	19
Payload bay diameter [m]	5.5	10	10
Height [m]	93	107	111
Est. Cost	\$63M	\$438M	N/A

In addition, we will use CEV (Crew Exploration Vehicle) (NASA, 2005) and LSAM (Lunar Surface Access Module) for transportation from Low Earth Orbit (LEO) to the lunar surface. CEV will be baselined as the lunar orbital vehicle and LSAM will be used for the lunar landing vehicle. At this point, LSAM is the only

publicly known planned human rated lunar landing vehicle under development. The CEV is launched by Ares I while LSAM is launched by Ares V.

With CEV and LSAM, the transportation strategy is outlined in Figure 2.4-1 (GAO, 2006). First, the LSAM and CEV rendezvous after being launched separately and head for the Moon. The CEV will remain in lunar orbit. The function of the CEV is to shuttle between LEO and lunar orbit, while the LSAM will shuttle between lunar orbit and lunar surface. Cargo can be launched directly to the Moon by Ares V using a cargo version of the LSAM to land on the lunar surface.

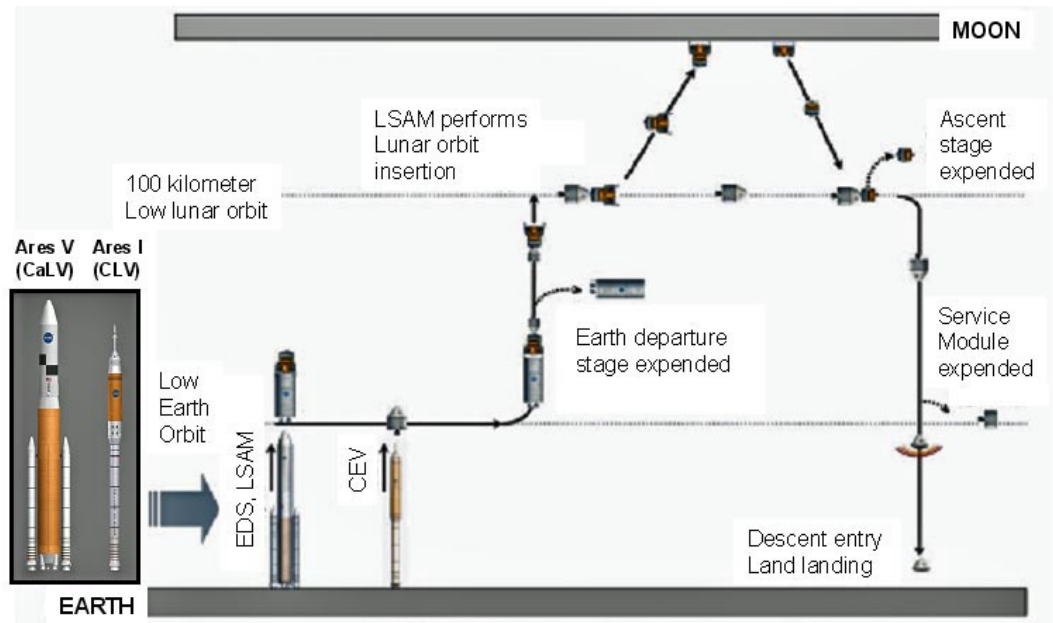


Figure 2.4-1 Launch Strategy

The LSAM is a limiting factors in this proposal as the only human rated lunar landing vehicle. Therefore, an LSAM adapter for Soyuz that it could be used as a rescue vehicle for LSAM or could be used instead of the CEV to meet the LSAM to lunar orbit is necessary. Thus, if there was a problem with the CEV while in lunar orbit, Soyuz could be used as an alternate vehicle to return to Earth. Additionally, other lunar landers strictly designed for delivering cargo may be developed that would be more cost effective than using a human-rated vehicle platform for LSAM.

## 2.4.2 Build Philosophy

The lunar base habitat philosophy will significantly impact transportation systems. Variables such as the size of the intended habitat, the area of the base, human or robotic missions, landing point, location of the lunar base and the build logistics including order of construction, and the method of assembly, all have a big impact on transportation logistics.

As described in the Architecture and Concept of Operations sections, a series of Ares I, Ares V, and cargo re-supply missions will be required for transportation. Estimated payload includes food, water, atmosphere, EVA equipment, scientific devices, subsystems, rovers, robots, habitat modules, materials for building the lunar habitat, nuclear reactor, machinery, and shielding against radiation and dust.

Table 2.4-2 (Corporation, 2002) shows mass and launch cost estimate of the Preliminary Phase based on the four precursor missions detailed in the Concept of Operations. In this phase, Taurus and Delta II were used as vehicles appropriate for the mass of payloads estimated for those missions based on previous and planned landers to the Moon and Mars.

**Table 2.4-2 Mass and Launch Cost Estimate of Preliminary Phase**

Precursor Mission	Mass to Moon [kg]	Mass to LEO [kg]	Vehicle Class	Est. Launch Cost [M\$]
Solar Thermal Rover 1	200	1200	Taurus	19
Rover 2	200	1200	Taurus	19
Mining/ISRU	900	5400	Delta II	55

Table 2.4-3 shows flight logistics for Luna Gaia assembly missions with the number of phases, flights and mission included. The missions required to build up the lunar base architecture are categorized into 4 phases. Refer to the Concept of Operations (Section 1.2) for the detailed description of the precursor missions and phasing as well as a general description of the construction phases. The concepts described in that section were used to generate the transportation requirements detailed here.

**Table 2.4-3 Flight Logistics for Construction Phase**

Phase No.	Years in Phase	Ares I Flights	Ares V Flights	Resupply	Mission
I	7	0	2 per year	0	Robotic cargo delivery and assembly
II	2	1 every 6 months	2 per year	2 per year	Human and Robotic Assembly
III	2	1 every 6 months	2 per year	2 per year	Introduction of Bioregenerative Systems with partial crew
IV	N/A	1 every 6 months	0	3 per year	12 person permanent settlement (re-supply)

For the purposes of international cooperation and for increasing redundancy, several existing launch vehicles could be used as more inexpensive alternatives for re-supply. Table 2.4-4 (Isakowitz, 2000) shows the comparisons of cost and launch abilities for some of these existing vehicles facilitating the selection of the least expensive launcher. There are many more which could be used as well. To take advantage of these options though, a simple cargo landing vehicle and transfer stage should be developed to enable to cargo to transfer from LEO to the lunar surface. The logistics are summarized in Table 2.4-4 and the main purpose of this summary is to give further options to carry payload to LEO at reduced cost compared to man-rated launch vehicles such as the Ares series. As an estimate for re-supply, we have made the assumption that the proposed closed loop life support system will allow for logistical re-supply on the order of 10% of

that required for ISS Expedition crew members. Using this estimate with Russian Progress modules (Gugliotta, 2006) and the re-supply mass provided on three missions per year for two ISS crew members recently, this results in an estimated re-supply mass for Luna Gaia of 450kg/person per year and thus approximately 5 metric tons per year to the Moon. That requires approximately 30 metric tons per year to LEO, so this puts yearly re-supply options within reasonable range of vehicles on the lower cost end of Table 2.4-5 using three launches per year. As a result, an average launch cost between Soyuz, CZ-3A, and H-IIA will be used of \$60M for budget planning purposes.

**Table 2.4-4 Transportation Scheme for Luna Gaia**

Section of Flight	Crew	Cargo
Earth to LEO	Ares I, Soyuz	Ares V, H-2A, Soyuz, Proton, Ariane 5, CZ-3A
LEO to Lunar Orbit	CEV, Soyuz/LSAM	CEV
Lunar Orbit to Lunar Surface	LSAM	LSAM
Earth to Moon (directly)	N/A	Ares V
Rescue (from Moon to Earth)	LSAM (docking with CEV or Soyuz at lunar orbit)	N/A

**Table 2.4-5 Cost and Launch Ability Comparisons of Existing Vehicles**

Launcher	Proton M	Soyuz	CZ-3A	Ariane – 5	H – IIA
Nation	Russia	Russia	China	Europe	Japan
Cost [\$M]	100~112	30 ~ 50	35 ~ 45	150 ~ 180	75 ~ 95
Mass launch ability to LEO (t)	21	6.9	8.5	22.6	10

After landing at the our recommended location on the lunar surface, surface vehicles will be required to deliver materials and equipment for building Luna Gaia. The following section will address lunar surface vehicles and other transportation needs.

### 2.4.3 Other Transportation Needs

Several other transportation systems will be required to support activities for the lunar settlement. Lunar surface vehicles are required to deliver materials to the habitat, and to aid in exploration and ISRU. In this section we will focus on surface vehicles and emergency vehicles. Requirements include (1) automated, autonomous robots, (2) remotely controlled systems (3) human-operated vehicles, as well as (4) human-robotics operated vehicles (Eckart, 1999).

At the lunar surface, a wheeled lunar rover or a caterpillar type vehicle would be most suitable to navigate the many different types of lunar terrain. Some of the terrain types include sandy areas, mountainous areas, cliff areas, crater areas and so on, thus vehicles with many wheels have the flexibility required for surface activity. In terms of delivering cargo, vehicles with relatively light cargo bays and heavy caterpillar treads are most suitable, enabling dual use of the navigation vehicles. The most attractive power source for these surface vehicles will be fuel cells with solar, chemical, electric and battery power sources used for redundancy. An advantage of fuel cells is their ability to be recharged by ISRU materials.

In terms of radiation shielding, if the exploration or construction mission is fully automated, shielding options are unnecessary. On the other hand, in case of manned missions, radiation shielding provisions are necessary. Human sorties across the lunar surface involve the risk of increased radiation exposure. GCR (Galactic Cosmic Rays) exposure will be continuous at relatively low levels similar to that experienced at the habitat. However, the greatest radiation concern during lunar sorties is solar radiation emitted from a solar flare event. Short-term exposure can be extremely high and warning of such an event could be limited to 20 minutes or less. Therefore, mitigation strategies need to be in place to protect astronauts from radiation exposure with short notice. Shielding of 2.0g/cm<sup>2</sup> is thought to be enough to protect crews from all but the largest solar flares (Harding, 1989), thus the crew vehicles will be equipped with a minimum of 2.0g/cm<sup>2</sup> of shielding. Aluminum is a good shielding source since it is relatively light weight, with a shielding of 2.7 g/cm<sup>2</sup>. As a result it is recommended that surface vehicles have walls with a minimum of 2 cm thickness to minimize radiation risk, particularly solar radiation risk. As a final potential mitigation strategy, pharmaceutical agents can be used to reduce the physiological effects of radiation on astronauts during lunar sorties. This possibility is addressed in Section 3.4 on Radiation.

For the emergency system, emergency capsules with solid rocket boosters and lunar surface emergency modules were considered. Lunar surface emergency modules are similar to surface rovers. These vehicles are attached to CEV and LSAM. After landing, these escape modules or vehicles are included in the habitat. LSAM will be used for the return vehicle from the lunar surface to the Earth. However, the LSAM doesn't have the ability to get back to Earth, thus it will need to dock to a CEV in Lunar Orbit. In addition, the hard shielding wall of the LSAM can be used for shelter. Luna Gaia will be inhabited by a maximum of 11 people, so a single landed LSAM doesn't have sufficient ability for an emergency evacuation of all inhabitant since it has a maximum capacity of six. As such, several reserve LSAM's are necessary. In addition, this emergency vehicle should have communication abilities. If the emergency vehicle cannot launch, the lunar inhabitants should be able to send a rescue signal to earth and survive long enough to be rescued. However, there is a concern that only one type rescue vehicle is available. Therefore we recommend that another rescue vehicle be designed and made available as an alternate to the LSAM rescue option.

### *Space Suits*

The current generation of space suits is unsuitable for the lunar environment. This was observed during the Apollo missions when after several days of use the suits began to fail primarily due to lunar dust wear (Gugliotta, 2006). The suits also have limited mobility and dexterity. Luna Gaia requires a next generation of suits that will provide the user with great mobility, dexterity and has a reduced weight. Several emerging options for suits include lightweight flexible suits and suits that dock onto the habitat and allow its user to egress from the back directly into an airlock to prevent dust contamination. The most promising option is mechanical counter pressure (MCP) suits to pressurize the skin as they provide significant advantages including reduced weight, great mobility and dexterity and reduced metabolic cost. However these suits have not been perfected and future research should be directed towards MCP suit development.

#### **2.4.4 Recommendations**

Primary transportation recommendation to facilitate the success of achieving Luna Gaia can be summarized as follows:

- Develop an interface adapter between Soyuz and the planned LSAM to allow an alternate crew rescue vehicle.
- Develop an alternate human-rated lunar lander to provide an alternate to LSAM.
- Develop a standard commercial lunar lander and transfer stage to get cargo from LEO to the lunar surface to allow for commercial and international launch options at a lower cost than human-rated vehicles incur.
- Develop another rescue/emergency vehicle as an alternative to the LSAM.
- Develop a new spacesuit which is better adapted to the lunar environment and the activities to be performed during lunar missions

# Closed Loop Habitat Design

## 3.1 Design Architecture

Architecture, which is the realistic integration and balance of a lunar habitat. It takes into account the realistic integration and balance of all systems in the total environment: social, economical, mechanical and operational. . Although affected by all the factors addressed in this report, the architecture of Luna Gaia can be categorized under the areas which follow.

### 3.1.1 Construction Type

#### *Structure Location:*

Due to the inherent concerns regarding safety, it is necessary to discuss what percentage (if any) of the structure shall be housed 'below ground,' as well as the benefits and drawbacks of each decision. The four basic configurations shown in Figure 3.1-1 were considered and the advantages and disadvantages weighed in Table 3.1-1:

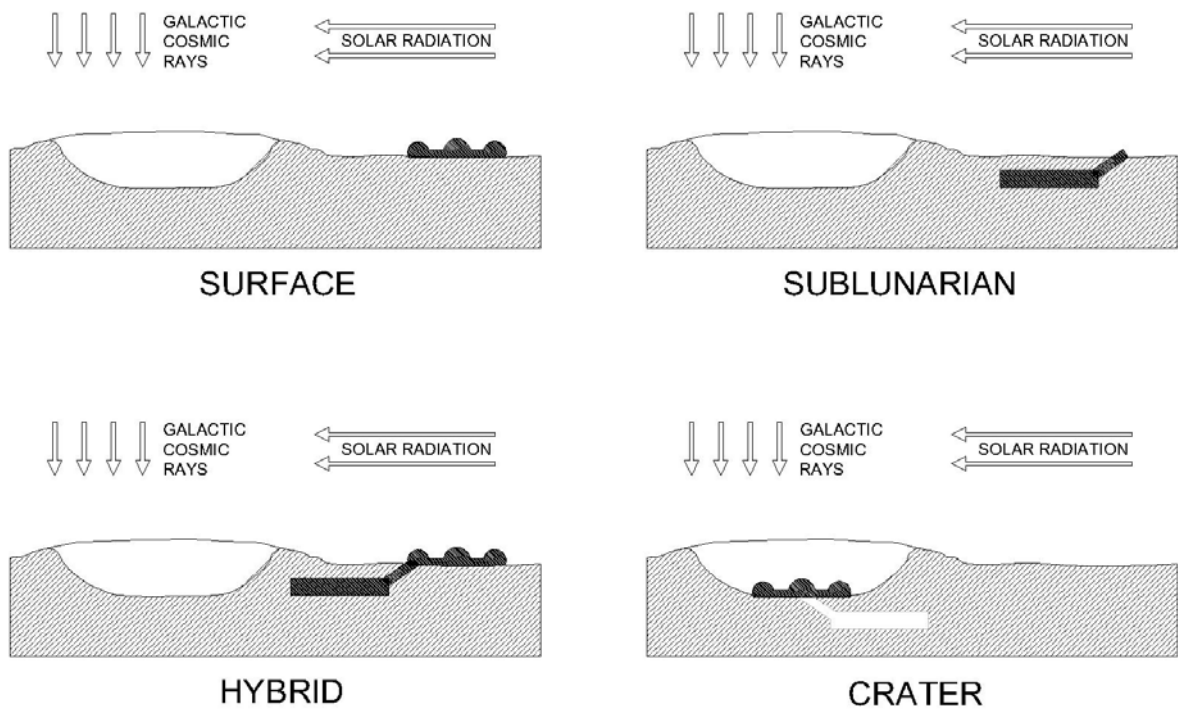


Figure 3.1-1 Lunar Location Options at Polar Latitudes

- A surface base, where the entire structure is situated above the existing surface of the Moon (only foundations and services, etc., are being considered below the stated level);
- A sub-lunar base, where the entire structure is housed below the surface level of the Moon;
- A hybrid base, which combines the beneficial features of both subterranean and surface construction designs; and,
- A crater base, which situates the base at ground level of an existing crater, but below the general surface level of the Moon, and integrates the structure with the surrounding environment.

**Table 3.1-1 Advantages and Disadvantages of Different Base Configurations**

Option	Advantages	Disadvantages
<b>Surface base</b>	<ul style="list-style-type: none"> <li>- Easy to set up (only foundations needed below ground).</li> <li>- Ease of access to majority of lunar surface</li> </ul>	<ul style="list-style-type: none"> <li>- Structure is exposed to radiation sources (both GCRs &amp; SW), &amp; also to micrometeoroid impacts</li> </ul>
<b>Sub-Lunar base</b>	<ul style="list-style-type: none"> <li>- Structure is protected from radiation sources (GCRs &amp; SW) &amp; also from micrometeoroid impacts</li> </ul>	<ul style="list-style-type: none"> <li>- Difficult to set up (mining on lunar environment is costly and difficult)</li> </ul>
<b>Hybrid base</b>	<ul style="list-style-type: none"> <li>- Advantages for different sections as per surface &amp; sub-lunar</li> </ul>	<ul style="list-style-type: none"> <li>- Disadvantages for different sections as per surface &amp; sub-lunar</li> </ul>
<b>Crater base</b>	<ul style="list-style-type: none"> <li>- Easy to set up as per surface base.</li> <li>- Structure is protected from Radiation sources (SW)</li> <li>- Use of regolith to cover base &lt;see radiation section&gt; now provides added ease of cover to protect from radiation sources (GCRs) &amp; also from micrometeoroid impacts</li> <li>- Possibility of a sub-lunar component for heightened safety (especially for extreme situations)</li> </ul>	<ul style="list-style-type: none"> <li>- Access to rest of lunar surface (besides crater) is more difficult, as infrastructure needs to be set up</li> <li>In case of a crater in eternal darkness, light needs to be captured for eco-habitats of the micro-colony</li> <li>Very cold temperatures (in order of ~40K) are experienced in a crater in eternal darkness, therefore some form of thermal regulation needed within structure</li> </ul>

The option decided best suited to our goals was the Crater base, which provided maximum benefits out of all possibilities.

### *Modular Design*

For increased success of Luna Gaia, the micro-colony must be of a highly adaptable and expandable design, modular in its essence, and remain as simple as possible, as illustrated in Figure 3.1-2. This allows for the future of further lunar colonization to be developed from the Luna Gaia modular platform, and is a driving force of the project.



This approach also provides some added benefits:

- The settlers of Luna Gaia are more easily able to adapt the interior environments of the micro-colony to their required needs, and make the spaces as functional and comfortable as possible. This provide the psychological bonus of fluidity to the design, so settlers escape the rigid feeling often associated with the ‘man in a tin can’ approach to space construction.
- Due to its modular design, added sections can easily be sold and incorporated into the functioning of the micro-colony, giving rise to commercial expansion possibilities.

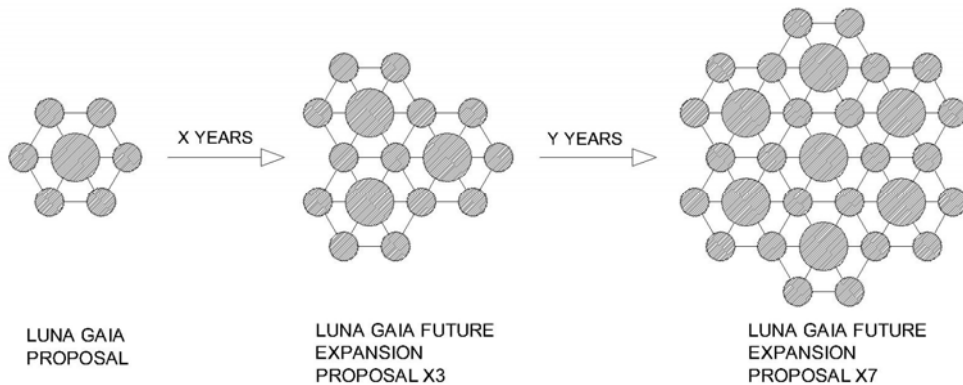


Figure 3.1-2 Expandable Design

### Structural Form

One of the proposed design solutions for Luna Gaia suggests that the main modular habitats be composed in buckminsterfullerene-type structural domes (Figure 3.1-3) (a concept derived from the structural stability of the carbon 60 molecule). This design provides a stable structure capable of withstanding the necessary loads, and the geometry involved can also be made into foldable units that expand to generate the overall space. Each constituent component is of a standard section, which provides huge benefits in terms of pre-manufacturing and assembly.

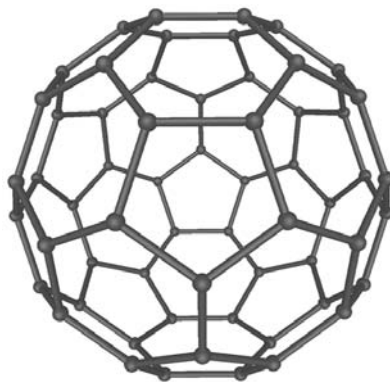


Figure 3.1-3 Buckminsterfullerene or ‘Bucky-ball’

This structure is a highly adaptable platform, and it can be molded to form many required shapes/volumes (i.e. cylindrical versions, flat versions, etc.).

### 3.1.2 Construction Technologies

#### *Research and Development (R&D):*

In the years leading up to the initial stages of each phase of the Luna Gaia project, research and development (R&D) is essential to furthering technology needed for each stage, and to test the proposed modular habitat designs in terrestrial extreme environments as well as testing the proposed building materials in the lunar environment.

#### *Inflatable Technologies:*

One of main issues in designing a lunar base is related to mass and volume transportation, not only because of launch vehicle limitations but also because of the ripple effect it has on other factors such as cost and timeline. Because of this, the issues of mass and volume clearly are key drivers to the lunar habitat design. An important example to note is that most flights on NASA's Space Shuttle are volume limited rather than weight limited. In light of this fact, it is wise to take the launching philosophy and vehicle into account very early in the design process to maximize the payload's volume to mass ratio.

In an attempt to resolve the driving forces behind this problem, alternative technologies from the standards existing today have to be examined for a solution. A possible solution discussed in the last several years is the innovative idea of inflatable modular structures such as those being invested in heavily by such figures as Robert Bigelow, and NASA.

*"It can cost from \$5,000 to \$50,000 per pound to put an object into space... Because inflatable structures minimize mass and volume, they are far less expensive and will become increasingly important in near-term and future space missions." [Larry Roe] (Scott R. Witherspoon, 2001)*

NASA has recognized the potential of inflatable structures for years. In the early days of the space program, NASA built a variety of inflatable satellites. These included, for example, passive communication satellites (Echo I & II), upper atmospheric density experiments (Explorer IX & XIX), and an Earth metric measurements satellite PAGEOS (Thomas).

Currently, NASA is providing ongoing technical assistance to a company named Bigelow Aerospace through Johnson Space Centre (JSC), where the TransHab ISS module was developed in 1997 before being cancelled (NASA). Bigelow is committed to the development of orbiting commercial inflatable modules by the end of this decade, with the possibility of JSC later using the technology for inflatable modules on the Moon.

Like many new technologies, it comes with some great advantages but also still has real disadvantages because it is not mature. Inflatable structures have the following benefits and drawbacks in their current state of development:

#### Benefits:

- Inflatables are attractive because they offer large in-use volume with enormous launch weight savings, lower packaging volume, ruggedness (the ability to withstand nuclear blasts, for example), and ease in making curved surfaces (Covault, 2004).

Drawbacks:

- With current technology, the hydrocarbon films used to construct these modules degrade when exposed for long durations to high energy particles and intense UV radiation. Mylar, for example, becomes brittle and opaque.
- Integration of windows and hatches into these structures has yet to be resolved. A major issue currently under development by Bigelow is how to fold and package the flexible material so once inflated in space, creases and folds and critical seals around windows and hatches do not leak. This is a major challenge on which there is little literature. Bigelow is currently doing extensive testing to obtain such baseline data.

This technology is relatively new and immature at present. However, it has recently been the subject of much scientific scrutiny to evaluate all the issues needed to be tackled to make this a viable technology.

In addition to the early NASA experiments and TransHab concept, the only inflatable to be tested so far, Genesis I, was recently launched by Bigelow (*July 2006*) and set in orbit. This test module, measuring  $\sim 2.5 \times 3$  m is the first of two planned Genesis flights to test the innovative inflation, pressure vessel and woven bladder restraint system of the Bigelow design. A key test will be the ability of the module to hold 52kP. pressure over time. So far, it was reported that the module inflated successfully, and records an internal temperature of 26°C.

A concern that arises with inflatables, however, is the vital issue of space debris and micrometeoroid impacts. The inflatable's outer surface acts like a bumper which shatters the meteoroid. For conventional structures these smaller fragments cause few problems. For the thin film inflatables the impact tests showed that the effect of this shattering was to magnify the damage on the next surface hit. In order to protect against this effect, an intermediate thin film is needed to catch and absorb most of these shattered fragments. Based on this, the inflatable was made from a five-layer micrometeorite shield constructed partly of carbon-fiber composites, but using a less costly design than similar NASA shields. This skin has only been tested terrestrially to date. For example, more than 50 ballistics at the University of Dayton Research Institute and the University of Denver Research Institute were devoted to firing particles of 0.64 - 1.5 cm toward the Bigelow shield at velocities ranging from about 3 – 7 km/sec. "The test showed we have a shield that performs comparably to NASA's, but at a fraction of the cost" [Brian Aiken] (Covault, 2004).

The emergence of Micro-Electro-Mechanical Systems (MEMS) technology will enable the modules to be monitored for pressurization, micrometeoroid impacts and vibration to name but a few. Sensors can be embedded between the skin layers and monitor the status of the habitat. Research is currently underway to allow the sensors to also take corrective actions (Witherspoon et al., 2001).

In the near future, however, the tests with the Genesis modules are to be followed by space tests with two "Guardian" one-third-scale inflatable modules carrying critical life support system demo hardware, due to launch in 2007.

*"We are a 100% experimental program, and we have to prepare for failures and not be overly shocked if they happen. We realize all of this is going to be done at significant risk."* [Robert T. Bigelow] (Covault, 2004)

Due to the current uncertainties with the technology and the need for more development work, we chose to use a legacy (ISS-like hybrid materials) structure

as the baseline for the base. However, the concept introduced in this section was designed with the flexibility to accommodate inflatable structures in part or in whole because the advantages are undeniably attractive (See Section 1.2, Concept of Operations for more info on the projected mass benefits and related cost improvements). Based on this tradeoff analysis, it can be concluded that accelerating the maturing process of inflatable structure technology should be an area of focus to make this project a reality.

#### *Automation:*

As much of the construction and running of the micro-colony should be as automated as possible through utilization of robotic builders and task drones. This allows the inhabitants to focus their time and effort away from mundane tasks (such as, for example, EVAs to retrieve re-supply cargos, regulation of the closed loop life support system, etc) and to focus on more important tasks like science, agriculture, and maintenance, etc. This also reduces the EVA time necessary for each of the mission crew, and reduces exposure to radiation.

#### *Building Structure & Skin:*

There are 4 main aspects regarding material choice which should be considered here:

- Radiation shielding,
- Thermal insulation,
- Heat resistance, and
- Low-thermal coefficient

Two materials, thus far, that can form the main construction materials are:

- Opaque habitats: Carbon Fiber Reinforcement Plastic (CFRP). This material is the strongest and lightest material that would be most beneficial to the construction of the base, and is already a proven technology. This, added with the benefits of carbon plastics in terms of radiation protection, makes this a possible choice for Luna Gaia [see Section 3.5 Safety].
- Transparent habitats: Glass Fiber Reinforcement Plastic (GFRP). Commonly called fiberglass, this is similar to CFRP [above], but is a transparent material much like regular glass, providing possible applications to the green house sections.

In addition, construction materials may be harnessed from the in-situ resources location on the Moon itself. Examples discussed in Section 2.2.4 In-Situ Resource Utilization include:

- Basalt
- Silicon
- Titanium
- Iron.

### **3.1.3 Protection**

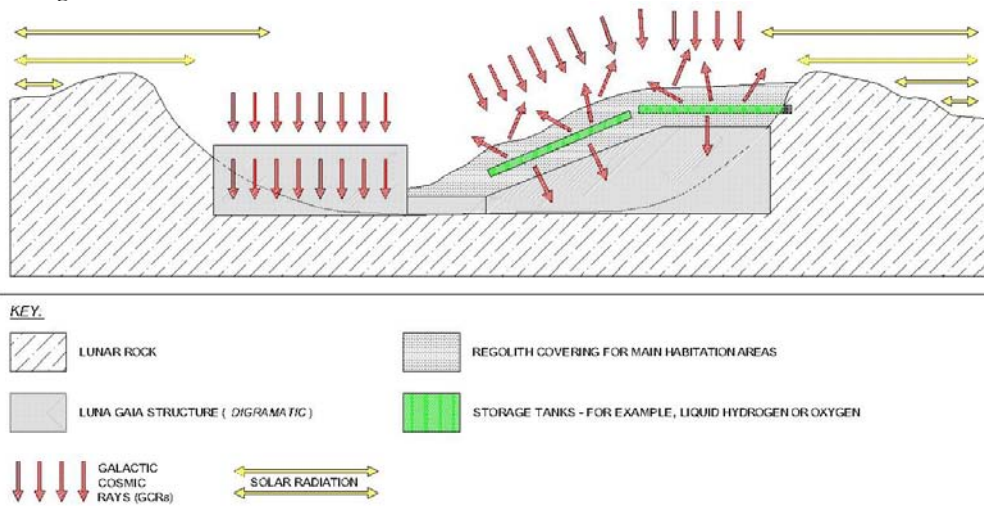
#### *Regolith Cover:*

Passive shielding will be adapted as the main form of shielding. Where possible, this will be aided by the use of lunar regolith as a protective layer covering the main habitat spaces where the colonists spend most of their time (i.e. living quarters, labs, etc). This will ensure that the inhabitants can be assured of

adequate protection, while cashing in on the benefits associated with use of the regolith. (For specific technical information, refer to Section 3.5, Safety).

*Storage Tanks:*

To best facilitate radiation protection, the use of material storage for radiation shielding is incorporated as safely as possible. Water is known for its high shielding properties, but other materials like hydrogen (in liquid form) are also beneficial for radiation protection. This may provide an interesting solution where the materials silo is incorporated above or around the general vicinity of the living and work modules. If nuclear power is used, then another possible consideration is to put the materials silo some safe distance between the reactor and the base, to help reduce any radiation concerns due to the nuclear fission reactor. This has a high degree of risk involved of course, but certain measures can be incorporated (especially separation of combustible elements from thermal contact with the structure). If this is a solution, then the hydrogen and other ideal gases harnessed from the Moon for use as fuel, for example, can be stored in this manner. See Figure 3.1-4.



**Figure 3.1-4 Radiation Protection**

*Micrometeoroid Impacts*

Due to the low risk of impact (the probability for meteoroid masses about 1 g hitting an area ~1 m<sup>2</sup> is ~1 chance in 10<sup>6</sup> - 10<sup>8</sup> in any one year), designing around micrometeoroid impacts is not critical (Eckart, 1999).

In this case, the risk is commonly expressed as some compound measure of both probability and consequences. The current probability of impact by meteoroids of particular sizes are now fairly well known, but the consequences of damage will depend very much on the nature and function of each component of the lunar habitat.

The material to build the modules, and the regolith to cover it, can provide sufficient protection against impacts for the habitat modules. External and delicate elements, however, such as solar panels and mirrors (as discussed in operations concept), should be designed taking into account reinforcement, redundancy and accessibility/repairability. The main Luna Gaia building structure is also designed to be easily repairable or replaceable as much as possible.

### *Safe House*

For protection, the “safe house” concept - a location in the base where, in case of disaster, the crew can safely hide out for a certain period and await safe recovery – is to be designed so it is accessible both from inside and outside Luna Gaia. This way, both crew on EVA and inside can enter the “safe house” for protection, but must be isolated from each other. This is of greater importance for EVA crew, as it means they can be safe long before they have to depressurize and de-suit whilst coming from EVA.

This safe haven can be anywhere on the base. It can be above or below ground, or incorporated into the living areas (specifically the dormitories), in the form of annular water tubes (hollow cylinders full of water with outer skins ~15cm thick) around the dormitory. [For specific technical information, refer to Section 3.5, Safety]. This would be a last resort measure if evacuation procedures were not possible.

### *Escape*

LSAM is the planned landing vehicle of Project Constellation (NASA) that will allow astronauts to land on the lunar surface when flights to the Moon resume after 2015 (NASA, 2006b).

The LSAM used to transport the astronauts to Luna Gaia will be used in case of emergency as safe-boats, emphasizing the dual use aspect of the habitat. The LSAM modules will be connected to Luna Gaia so that these escape modules will be easily and readily accessible for any type of emergency and without need for an EVA. Modules like these, however, need constant maintenance, as they become unreliable as emergency escape modules if left sitting idle for too long. At the moment, it is proposed that two weeks is the maximum timeframe of reliability of the current technological solutions (The LEM modules of the Apollo program for example). For long term habitation to occur these technologies need to be further refined and developed and the modules themselves will have to be regularly serviced while *in situ* on Luna Gaia.

### *Size:*

The size of the base will be determined heavily by the areas required by humans to live in comfortably and healthily. Some figures of area as per activity are stated in Table 3.1-2. To better minimize the overall area of the base, and cut down on mass/volume and hence cost, a policy of converging and overlaying similar areas (as ascertained from the zoning diagram) to make dual use of space has been adapted into Luna Gaia. This is not carried out at the expense of a specific activity however. All the vital areas are kept at the recommended levels, as much as is feasible. This combined use of spaces for activities also extends to the incorporation of the closed loop life support system space requirements.

## **3.1.4 Incorporation of Closed Loop Systems**

A ‘circular’ system - in terms of closed loop water and atmosphere – has been incorporated into the design as much as is seen to be beneficial to the entire CLLSS and architectural integration.

*Water cycle:*

The water cycle is done in a number of loop cycles (figure 3.1-5 ii): one overall loop which forms the main cycle, which is comprised of the two smaller loops to allow for redundancy in case of malfunction, adaptability, and further closed loop scientific study.

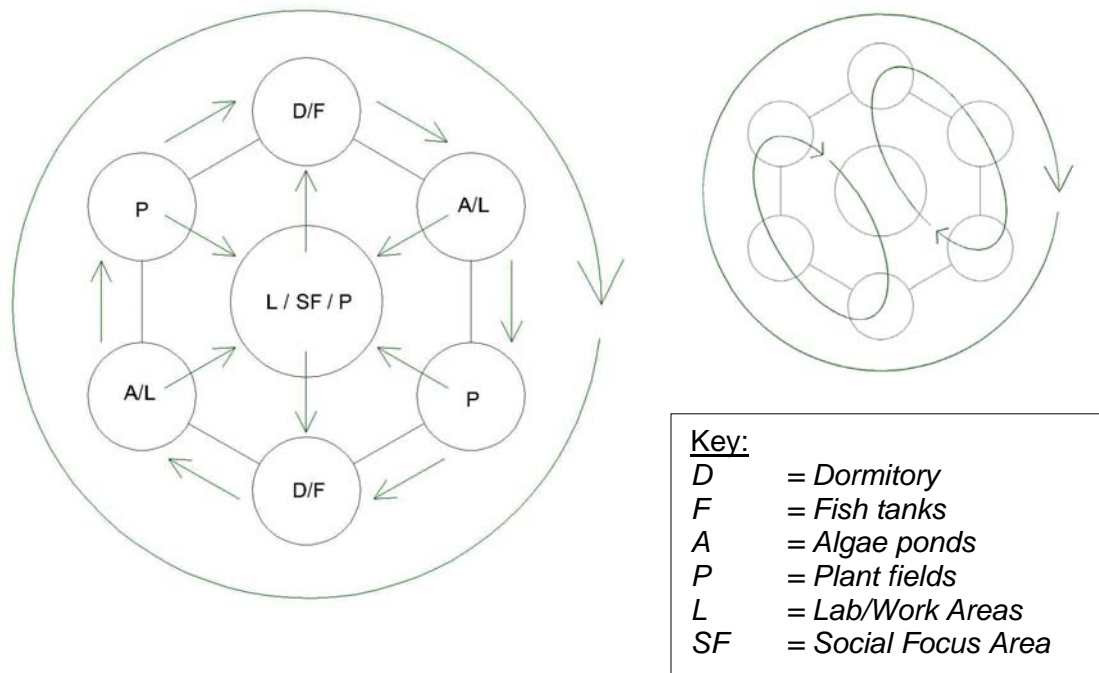
**Table 3.1-2 Lunar Base Space Requirements**

Activity	NASA ExPO *	Luna Gaia
	(m <sup>2</sup> )	(m <sup>2</sup> )
Food storage	7.9	3
Galley	9.35	9.5
Wardroom	18.67	10
Recreation	44.37	42
Exercise	7.18	8
Health maintenance	19.15	19
Hygiene	17.4	17.5
Laundry	3.1	3
Crew Quarters	45.2	80
Exterior view	1.97	2
Viewing area	20	10
Storage	25	25
Command	22.2	22
Telerobotics	44.4	22
Landing operation	44.4	22
General Lab	18.7	19
Biochemical Lab	14.55	14.5
Microbiology Lab	18.7	18.5
Plant Growth Lab	24.15	N/A (using a CLLSS)
Maintenance	9.45	9.5
Safe haven	42.45	42.5
EVA Storage	18.75	18.5
<b>Total</b>	477.04	441.5
<b>Net Growth @ 25%**</b>	119.26	110.4
<b>Total with 25%</b>	596.3	551.9

Notes:

\* The 1992 NASA ExPO human-tended outpost for 12 crew members (Eckart, 1999).

\*\* The 25% multiplier is for circulation, mechanical and electrical standoffs, and walls. The "total with 25%" is the gross size for the habitat as a whole.



**Figure 3.1-5 i) Closed Loop Water Cycle Integration. ii) General Closed Loop Water Cycles**

To achieve this, the dormitory areas must be higher than both the algae, and the plant habitats, to facilitate gravitational flow of the water. The areas required for each of these elements is broken down as follows: [For precise figures, see Section 3.2, Closed Loop]

- Plants and Algae, housed in transparent habitats.
- Dormitories with integrated fish tanks, housed in regolith-covered opaque habitats. (These tanks provide added psychological and radiation protection benefits for the inhabitants housed in the dormitories.)
- All similar habitats are located opposite each other, to set up the overall loops and smaller loop systems.

This double loop approach also allows the micro-colony's closed loop life support system to be set up in two major stages (each major loop). Construction and instigation of the micro-colony on a smaller level can thus be addressed initially, before proceeding to the overall design.

### *Atmospheric cycle*

A passive ventilation system will be investigated (and implemented if successful) into the Luna Gaia environment. This works on the basis that warmer areas of the micro-colony (e.g. greenhouses) will have their heated air rise up to the higher level colder areas (e.g. dormitories), and vice versa, in order to set up convection circuits of air throughout the whole environment. Along with this, the air will need to be filtered, especially between habitats, to avoid cross-contamination of modules.



### 3.1.5 Infrastructure

#### *Access*

Depending on the specific location chosen (i.e. a crater in this instance), and the characteristics of its surrounding ridges, it may be necessary to set up an infrastructure connecting Luna Gaia to the Moon's surface. This can be done through tunneling or the construction of 'roads', as shown in Figure 3.1-6.

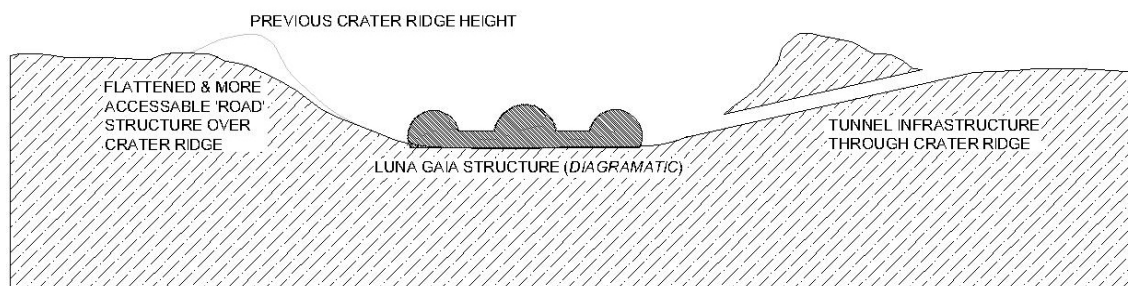


Figure 3.1-6 Infrastructure

### 3.1.6 Design Considerations

Design considerations encompass all the issues regarding design of the micro-colony which need to be taken into consideration before arriving at a conceptual design framework.

*Modular human proportions* used by Le Corbusier in his architecture (figure 3.1-7) (Van Onck, 2006) are to be adapted, into the design of the spaces (specifically the dormitory spaces) to make them as humanly comfortable as is feasible. This, however, needs to be preceded by some study on the changes observed in humans of these bodily proportions (posture, height, etc.) in lunar gravity. Le Corbusier described the Modular as "a modest servant offered by mathematics to people desirous of harmony, a universal tool for all kinds of fabrications destined to be sent to all parts of the world. The Modular is based on human height... it places man at the centre of the drama, its solar plexus being the key to the three measures, which express the occupation of space by its members." (ChandigarhArchitecture, 2006)

Furthermore, the nominal 3 meter human gait observed in the lunar environment by the Apollo missions has been accommodated into the overall architecture of the micro-colony.

*Zoning*, or division of space type/function, is essential in a closed and limited volume environment such as Luna Gaia. This involves the relative placement and clustering of activities that have similar human requirements and separating them from other activities with conflicting requirements so that clear distinctions between work, living, and environmental spaces shall be maintained in the micro-colony by the incorporation of each of these similar elements into their own modular habitats.

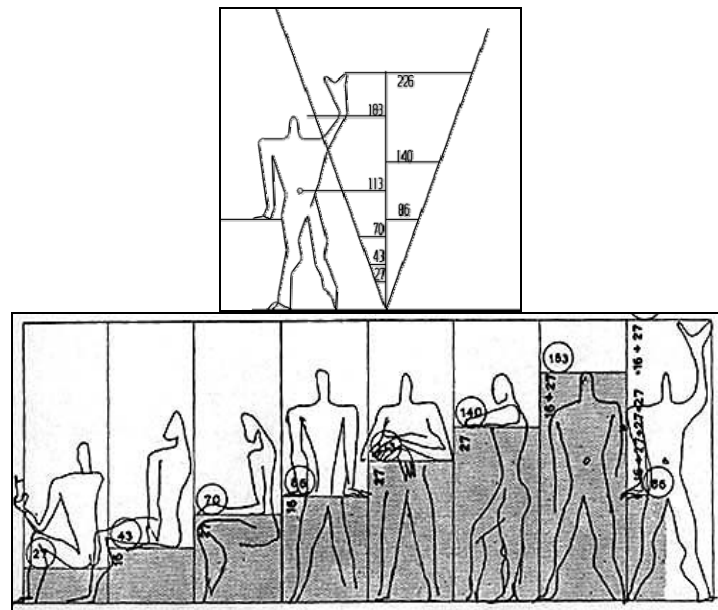


Figure 3.1-7 Modular Human Dimensions (Le Corbusier).

It is possible to construct a spatial compatibility matrix to help determine which activities should be adjacent or separated, a.k.a. a 'zoning diagram'. In this diagram, two principal axes are considered:

- Quiet to Noisy (quiet activities need to be buffered from noisy ones), and;
- Private to Social (private activities can only occur if they are separated from group activities).

A list of all the activities that are required in the micro-colony has been done, and located into a zoning diagram, Figure 3.1-8 (Eckart, 1999). The activity spaces clustered together are compatible and Luna Gaia has been designed to house these activities in relative proximity to each other.

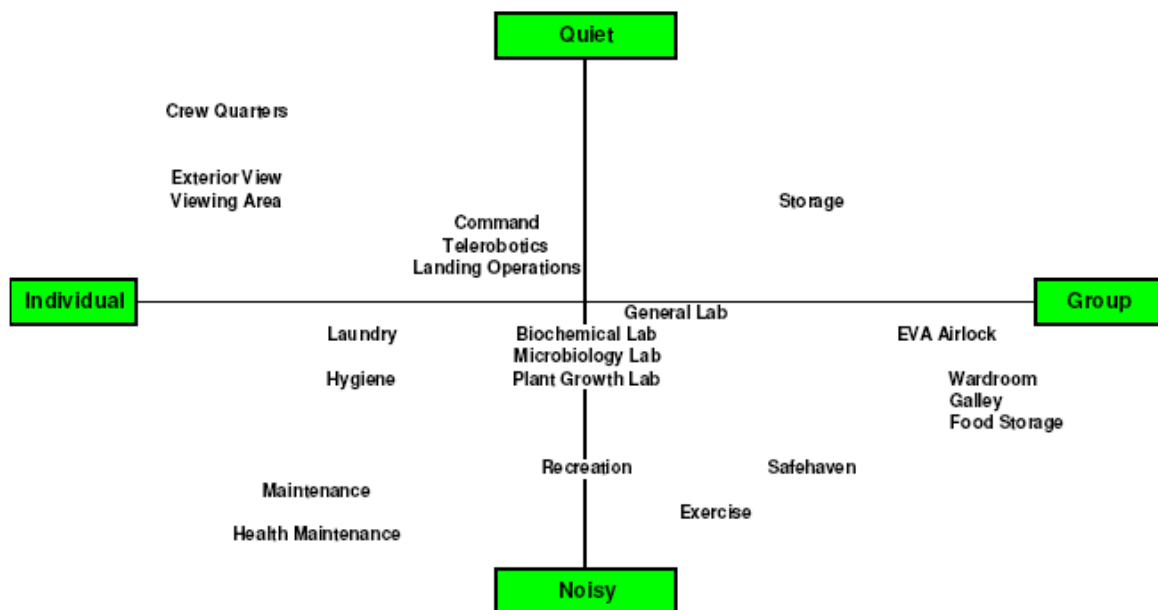


Figure 3.1-8 Zoning diagram

When incorporating activity zoning, it is essential for the well-being of the inhabitants not only for the provision, but also the delineation of *social and private spaces*. This practice requires the clear distinction between spaces of social

interaction (i.e. Galley), and those of more solitary natures (i.e. crew quarters). Luna Gaia comprises as a main focal point in its design a large social Earth-like environment, in which the micro-society can best integrate as a matrix. In addition to this, the inhabitant “dormitory” zones have, at its center, a kitchen space which is to act as the social driver in this environment, at a smaller level. Some redundancy in space and facilities is inbuilt here for the period of inhabitant changeover in the mission timeline, and thus to accommodate the temporary overflow of inhabitants on Luna Gaia.

To best achieve a successful zoning practice, it becomes an important human requirement (especially in a limited volume such as Luna Gaia) to transition between zones (living area, working area, social area, control centre, operations and storage facilities, etc.). The main purpose of transitioning is to facilitate the human tendency of normal daily rhythms which include, for example, transition time between home and job. This approach has been incorporated into the circulation zones between modular habitats in the following ways:

- Through use of mediating environments (for example, using environmental ‘green’ spaces to moderate between work and living zones).
- Use of the Japan concept of ‘engawa’ (a view that the interior and exterior of a space are not distinctly different environments, but are thought of as being continuous elements) can be used to integrate a flow and mix between spaces.
- Use of changing aesthetics in the transition space to delineate a change between the different spaces.
- All these elements add up to provide a basic framework of considerations on which to design Luna Gaia.

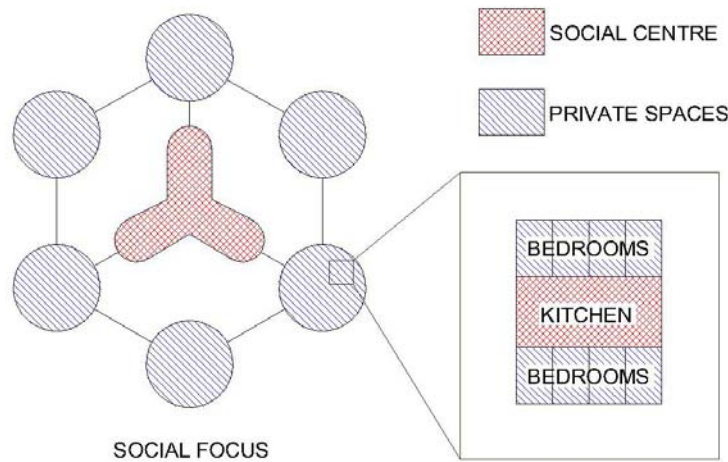


Figure 3.1-9 Social Focus

## 3.2 Closed Loop Life Support Systems

### 3.2.1 Introduction

The closed loop life support system provided by the Earth involves an incredibly complex interaction among many sciences: biology, geophysics, meteorology, biogeography, evolution, geology, geochemistry, hydrology and all the rest of life and Earth sciences. Imitating these processes is a challenge that has been previously attempted with limited success. However, Earth-based research such as the MELiSSA system which recycles water with 100% efficiency on the Concordia station in Antarctica demonstrates that closing a loop is possible.

For a lunar base, the need for a closed loop support system is driven by the provisioning from Earth which may come only once every 6 months with replacement lunar inhabitant personnel.

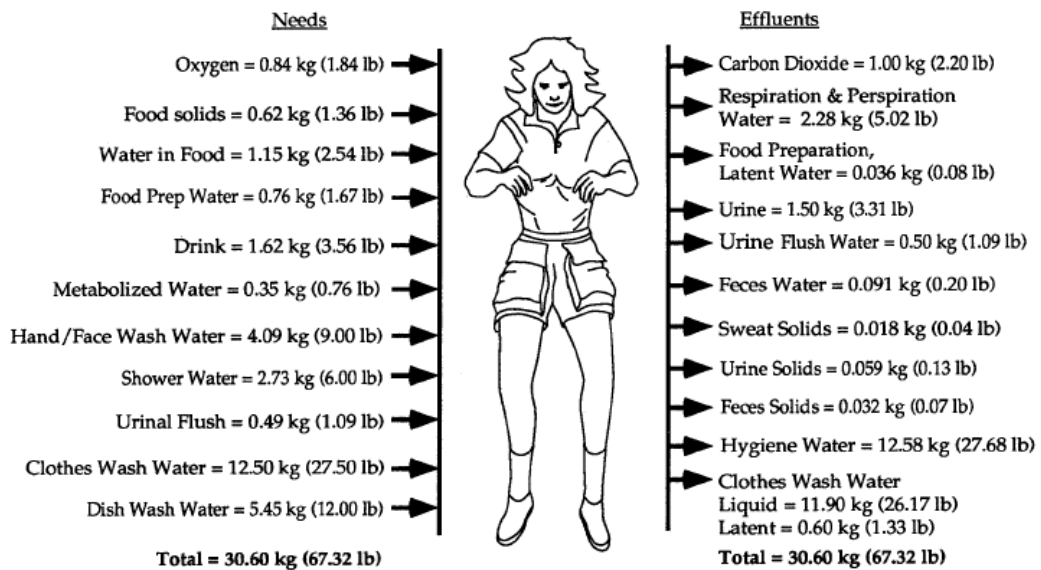
### 3.2.2 Human Requirements

The main consumables needed by the crew are oxygen, water, and food. The main outputs from the crew are CO<sub>2</sub>, urine, and feces. Table 3.2-1 demonstrates the different needs and effluents of a typical crew member.

#### Water Requirements

Potable and hygiene water must be provided for the crew. Table 3.2-1 summarizes water consumption per crewmember per day. Care must also be taken that the water be provided at temperatures suitable for use in food, cleaning and drinking. Cold water should be provided at 4 +/-3 °C for drinking, ambient water should be available at 21 +/-5 °C for general use and hot water should be available up to 65°C for food preparation.

Table 3.2-1 (Kubicek and Woolford, 1995) shows the daily requirements of a person whose daily metabolic rate is 136.7 W/person. However estimations are based on a particular population and differ between studies (e.g. the estimation by REGLISSE (Dussap, 2003) based on a person whose daily metabolic rate is 167 W/person). From this tablet we can say that an average person needs 1.97 kg of potable water and 25.26 kg of hygienic water per day. It is important to note, however, that the water coming from food is not counted.



Note: These values are based on an average metabolic rate of 136.7 W/person (11,200 Btu/person/day) and a respiration quotient of 0.87. The values will be higher when activity levels are greater and for larger than average people. The respiration quotient is the molar ratio of CO<sub>2</sub> generated to O<sub>2</sub> consumed.

Figure 3.2-1 Human Requirements Per Day

**Table 3.2-1 Summary of Water Consumption per Crewmember for Different Operational States**

Type of Water	Operation States	Water Consumed per Crewmember per Day
Potable	Nominal	5.16 kg
Potable	Off-nominal or otherwise degraded	2.84 kg
Hygiene	Nominal	23.4 kg
Hygiene	Off-nominal	8.18 kg
Hygiene	Degraded	5.45 kg

*Atmospheric Requirements*

Basic human input and output to and from the closed loop atmosphere are summarized in Table 3.2-2 (Division, 2003). The data is simplified to Oxygen, O<sub>2</sub>, and Carbon Dioxide, CO<sub>2</sub>, as the major affecting components.

Atmosphere Design Requirements

In engineering terms, atmospheric requirements of the lunar habitat are depicted in Table 3.2-3 (Division, 2003).

A person produces 1.0 kg CO<sub>2</sub> per day. If left unchecked, human usage will lead to the build-up of CO<sub>2</sub> and a deficiency of oxygen in a closed habitat. Methods such as CO<sub>2</sub> removal and O<sub>2</sub> generation must be employed to maintain sufficient atmospheric composition.

There is a trade off between habitat pressure and EVA space suit pressure that needs to be considered. A larger difference between these two pressures increases pre-breathe time prior to EVA. In the habitat, human performance is optimized at one atmosphere; however space suit pressures should optimally be kept at a lower pressure to provide higher mobility and dexterity.

**Table 3.2-2 Human Atmospheric Requirements**

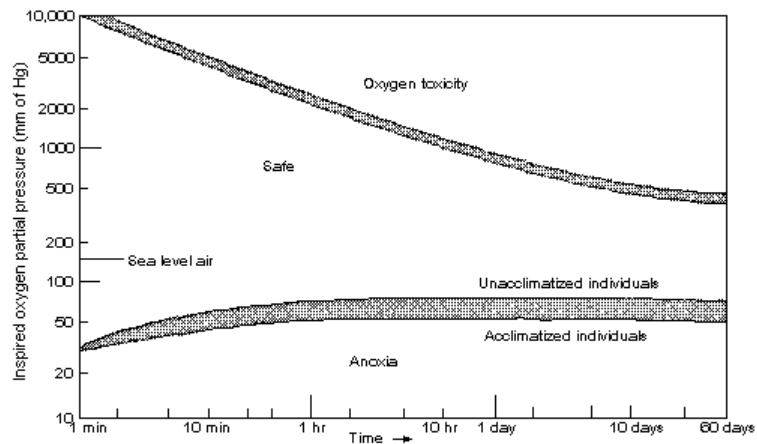
Category	Metabolic Load [kJ/(person-day)]	O <sub>2</sub> Consumed [kg/(person-day)]	CO <sub>2</sub> Produced [kg/(person-day)]
Low Activity Metabolic Load	10,965	0.78	0.93
Nominal Activity Metabolic Load	11,820	0.84	1.0
High Activity Metabolic Load	13,498	0.96	1.14
5th Percentile Nominal Female	7,590	0.52	0.62
95th Percentile Nominal Male	15,570	1.11	1.32

**Table 3.2-3 Lunar Atmosphere Design Requirements**

Atmosphere Component	Pressure
Total atmospheric pressure	0.42-1.03 Atm
O <sub>2</sub> partial pressure	21-50% O <sub>x</sub> volume
CO <sub>2</sub> partial pressure	0.18-0.23 Atm
	<0.01Atm

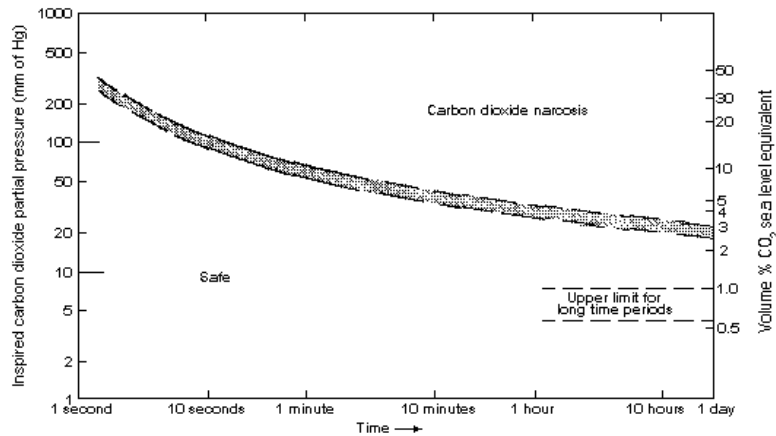
Another important aspect to the body’s ability to absorb oxygen from the atmosphere is the atmospheric pressure, specifically the partial pressure of oxygen (Figure 3.2-2). In an emergency situation, partial pressure of O<sub>2</sub> (pO<sub>2</sub>) can be as low as the partial pressure in the lungs, 0.156 atm. For normal breathing, the pO<sub>2</sub> within the habitat should be kept at a minimum of 0.204 atm. to avoid the affects of anoxia (Kubicek and Woolford, 1995). To avoid the flammability hazard experienced by Apollo 1, the partial pressure of oxygen should not exceed 30% of the air in the habitat (Shayler, 2000). For a 0.204 atm. partial pressure of oxygen equaling 30% of the atmosphere, the lowest total pressure of the habitat is 0.670 atm. If the habitat is kept at 1Atm, then the maximum pO<sub>2</sub> would be 0.200 atm. If the habitat is leaking and the leak rate is slow, symptoms of oxygen deprivation may include sleepiness, headache, sluggishness, the inability to perform simple tasks, and eventually loss of consciousness. In the event of a rapid decompression, the person will very quickly lose consciousness and not experience any of the early onset symptoms.

If the carbon dioxide reduction system malfunctions, symptoms of carbon dioxide narcosis will start to appear in amounts above 0.020-0.027 atm. partial pressure of carbon dioxide (Figure 3.2-3). For peak human performance the habitat will keep carbon dioxide partial pressure below 0.005-0.009 atm.



**Figure 3.2-2 Human Tolerance Time of Oxygen Partial Pressure**

If the habitat pressure is lowered, the percentage of oxygen increases, thus increasing flammability risk. If the habitat is kept a lower pressure for EVA considerations, it should be kept no lower than 0.670 atm, which would be a 30% oxygen concentration.



**Figure 3.2-3 Human Tolerance Time of Carbon Dioxide Partial Pressure**

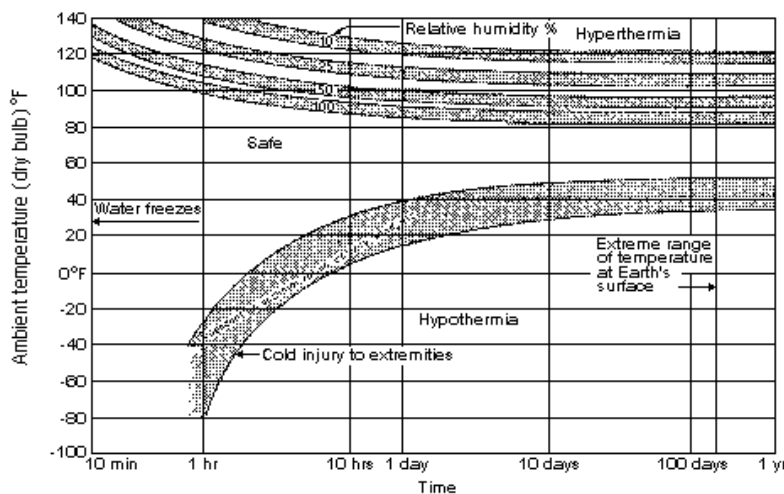
Habitat Temperature and Humidity Requirements

Temperature regulation within the habitat is compounded by the very high temperatures in the sun and very cold temperatures in the shade. When determining the level of heat into the closed system, all of the heat added to the system generated by equipment and human metabolic heat needs to be taken into account.

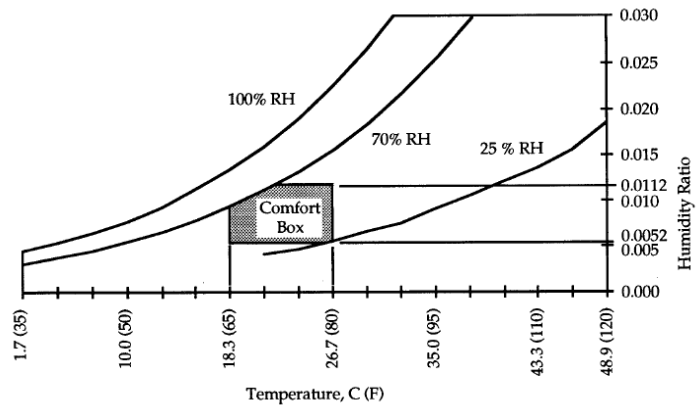
Humidity is also important to control for human comfort and plant growth as well as for prevention of shorts in electrical equipment caused by condensation. There are two methods of humidity control: collection of condensation and drying the air with a desiccant. A combination of these methods is regularly used.

Human respiration adds about 2.4 kg of water vapor per day to the atmosphere per person

For human performance and comfort, humidity and temperature need to be analyzed together. As shown in Figure 3.2-4 and Figure 3.2-5, the lunar habitat temperature should be maintained between 18 and 26 °C and relative humidity between 25 and 70% (Wieland, 1994).



**Figure 3.2-4 Human Tolerance Time to Temperature and Humidity**



**Figure 3.2-5 Human Comfort Levels to Temperature and Humidity**

### *Food Requirements*

The World Health Organization recommends a daily intake of 10 834 kJ for a typical person of 70kg. The formula used to calculate energy requirements in 1g are presented here (NASA, 2003b). It has been shown that the WHO recommended daily intake calculation using moderate activity level can be used in microgravity (Agriculture, 2005). The recommended daily nutrient intake of astronauts and cosmonauts varies between 9600 kJ/day and 13400 kJ/day (Eckart, 1994).

*Men (30 to 60 years): Activity  $((1.7) \times (11.6 W + 879)) \times 4186 = \text{kJ/day required}$*

*Women (30 to 60 years): Activity  $((1.6) \times (8.7 W + 829)) \times 4186 = \text{kJ/day required}$*

*where  $W = \text{mass (kg)}$  and the activity level is assumed to be medium, ranging from 1.0 to 2.0.*

Nutrients can be subdivided into three categories, each of them allowing for a fraction of the recommended daily energy supply. Carbohydrates can be found in grains, potatoes, rice and other sources and should account for 50-55% of the energy supply, for a total of 300-600g/crew-day (Eckart, 1994). Lipids are found in nuts, oil, meat and other sources and should account for 25-30% of the energy needs of humans, for a total of 50-150g/crew-day. It should be noted that essential fatty acids cannot be synthesized by the human body and must therefore be supplied through the diet. The minimum provision of essential fatty acids is 10g per day. Proteins provide the necessary building block required to support protein synthesis for metabolic activity. The energy derived from protein utilization should vary between 15-25%, for a total of 50-300g/crew-day. Essential amino-acids cannot be synthesized by the human body and should be provided in the diet (Eckart, 1994).

In order to meet these specified requirements, the USDA (United States Department of Agriculture) recommends a daily intake summarized in Table 3.2-4 (HW Lane, 1997).

Additionally, food variety is necessary for good crew morale over long-duration missions. A typical diet consisting of pre-packaged food similar to food provided on the ISS would represent a mass of approximately 1.83 kg per crewmember per day. However, to allow for a sustainable diet relying on carbohydrates and salad from food crops, the anticipated mass of food required per day is between 3.6-3.82 kg (NASA, 2003b).



**Table 3.2-4 USDA Recommended Daily Intake by Food Group.**

	Fruit	Vegetable	Grains	Meat and beans	Dairy/milk	Oil
<b>Daily intake</b>	473 ml	591 ml	170 g	156 g	710 ml	24 g
<b>Example</b>	Fruit, fruit juice	Vegetable, vegetable juice	Bread, rice, cereal	Meat, eggs, nuts, beans	Milk, cheese, yogurt	Margarine, oil, dressing

### 3.2.3 Specific Methods for CLLSS Technologies: ECLSS Technologies

In a manned space mission, the Environmental Control and Life Support System (ECLSS) must be able to support the daily needs of the crew members. The major problem areas include:

- Maintaining the cabin atmosphere
- Potable and waste water management/distribution
- Nourishment (food) for the crew members

There are many techniques that have been and can be used to close the loops. Technology options for life support systems are divided into two categories: physico-chemical and bioregenerative. Physico-chemical technology use fans, filters, physical or chemical separation, concentration process, etc. Bioregenerative technologies employ living organisms such as plants or microbes. Traditionally, missions have used physico-chemical processes because they are well understood, relatively compact, easy to maintain, and have quick response times.

#### *Specific methods for CLLSS technologies*

Re-supply has been used in the past because these missions have been short duration or located in close vicinity to the Earth where the penalty of storage and transportation does not have a great influence. However missions to establish permanent settlement on the Moon or Mars will have significant cost for transportation and the storage of consumables due to longer mission durations. But they cannot replenish food stocks. Biological processes are less well understood, take up large volumes, need more power and maintenance, and have a slow response time, but they can produce food and recycle wastes. For the lunar base, the macro life support system will be a hybrid design that incorporates both physico-chemical and bioregenerative processes (Larson and Pranke).

Numerous options are available for providing solutions to these problems, and these options have different degrees of cycle closure. The various degrees of cycle closure that exist are:

- Open cycle
- Partially closed loop
- Fully closed loop

In the following section, various methods aimed at closing the loops in ECLSS will be explored, beginning with an outline of physico-chemical processes and then proceeding to bioregenerative systems (Eckart, 1994).

### 3.2.4 Air

The methods presented here, are techniques, methods and technologies for atmospheric treatment. These methods include physico-chemical systems and bio-regeneration.

#### *Atmosphere Management*

Managing the atmosphere includes controlling pressure, temperature and humidity, ventilating and removing contaminants, monitoring the atmosphere's composition and replenishing gases (Mark Ayre, 2004).

Considering the long-term nature of the project, the atmospheric pressure within the lunar base living structures should be maintained at a level suitable for human health and function. Pressure control uses valves, regulators, and heaters, with control algorithms that use data provided by pressure sensors and the atmosphere monitoring system. Thermal control can be achieved by transferring internal heat loads and external heat fluxes to a water coolant loop. Humidity, generated by the crew or the CO<sub>2</sub> control unit, can be removed by decreasing the air temperature below its dew point and by separating the condensed water from air flow. Using fans, ducting, and isolation valves ventilate the chamber. Monitoring can be achieved by the traditional detection methods, such as gas chromatography, mass spectrometry, and infrared light. For partially or fully closed loops, the Air Revitalization System (ARS) is desirable. The subsystem functions of the ARS include three main processes: CO<sub>2</sub> removal, CO<sub>2</sub> reduction, and O<sub>2</sub> regeneration. Other important process considerations include: trace contaminant removal, makeup gas storage, and storage of recovered waste gas.

#### *Carbon Dioxide Removal*

There are five physico-chemical ways of removing CO<sub>2</sub>:

##### Four-Bed Molecular Sieve (4BMS)

Two sets of identical beds operate in parallel - one set for adsorbing and the other for desorbing. The zeolite bed contains 5A-zeolite which traps CO<sub>2</sub> by selective absorption. The desiccant bed containing silica gel (or 13A zeolite) is placed in front of the absorption bed to prevent water vapor from reaching the CO<sub>2</sub> adsorption bed. The beds switch functions when they reach storage capacity. They are heated to desorb water to the cabin and CO<sub>2</sub> to the Sabatier reactor (Kanghan, 1995).

##### Two-Bed Molecular Sieve (2BMS)

A two-bed hydrophobic molecular sieve has been designed to overcome the disadvantages of the 4BMS (Kanghan, 1995).

##### Electrochemical Depolarized Concentrator (EDC)

The EDC consists of a series of batteries that continually remove CO<sub>2</sub>. CO<sub>2</sub> and H<sub>2</sub> are passed through a battery. Alkaline electrolyte absorbs CO<sub>2</sub> to produce CO<sub>3</sub><sup>2-</sup> and HCO<sub>3</sub><sup>-</sup>. These ions then pass through the battery pole containing lacunar material and CO<sub>2</sub> is released due to the pH change (Alejandra Menchaca, 2005).

### Air Polarized Solid Amine Water Desorber (SAWD)

CO<sub>2</sub> scrubbing is achieved through adsorption with a weak alkali amine resin followed by CO<sub>2</sub> desorption by applying heat from a steam generator. Water is required in the process, as dry amine cannot directly react with CO<sub>2</sub>.

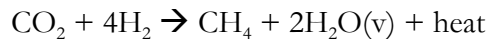
### Lithium Hydroxide (LiOH)

LiOH is used in breathing gas as a purification system for spacecrafts, submarines and rebreathers to remove CO<sub>2</sub> from exhaled gas by producing LiHCO<sub>3</sub> (Kliss, 2006b).

### *Carbon Dioxide Reduction*

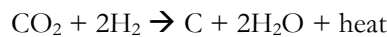
There are four main physico-chemical ways to reduce CO<sub>2</sub>, and at the same time regenerate O<sub>2</sub>:

#### Sabatier Process



The catalytic methanation reaction between CO<sub>2</sub> and H<sub>2</sub> gas, using high temperatures (450-800 K) and a Ni catalyst, is exothermic and self-sustainable. Water vapor generated can be recovered by passing product gases through a condensing heat exchanger. Water produced can be electrolyzed to produce O<sub>2</sub> for atmosphere and H<sub>2</sub> for recycling to the Sabatier reactor (Koelle, 2000).

#### Bosch Process



Exothermic reaction converts CO<sub>2</sub> and H<sub>2</sub> gas into C and H<sub>2</sub>O in presence of an Fe catalyst at temperatures 800-1000 K. The reaction usually results in partial conversion, from 30% at lower temperatures to 98% at higher temperatures (Gugliotta, 2006).

### Advanced Carbon Dioxide Reduction System (ACRS)

This Sabatier reaction converts CH<sub>4</sub> to C. ACRS is a gas/liquid separator and Carbon Formation Reactor (CFR) for CH<sub>4</sub> pyrolysis. CFR packs C better than the Bosch process but uses an operation temperature of 1100 K (Gugliotta, 2006).

### Carbon Dioxide Electrolysis (CDE) - Zirconia System

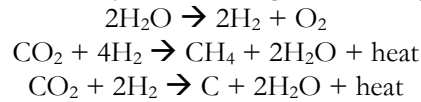
CO<sub>2</sub> electrolysis reduces CO<sub>2</sub> and produces O<sub>2</sub> by passing CO<sub>2</sub> through a zirconia electrolysis cell at 800-1000°C. Twenty to thirty percent of the CO<sub>2</sub> dissociates into O<sub>2</sub> and CO. Separation is achieved by electrochemical transport of the oxide ion through a membrane. The electrolysis system is based on the Tubular Monolithic Ceramic Oxygen Generator (TM-COG) platform, whereby multiple oxygen separation cells are connected in series across both faces of a porous, flat-tube support. Design allows for simplified gas manifolding, sealing, and current collection and permits higher cell stacking efficiency. O<sub>2</sub> may be used for life support and as an oxidant (for fuel cell power system), and CO may be collected and used directly as fuel (or converted to CH<sub>4</sub> for use as fuel) (Duffield, 2001).

## *Oxygen Regeneration*

There are mainly four ways to regenerate oxygen:

### Water Electrolysis

The equations for water electrolysis converting water to oxygen and hydrogen:



The water is supplied from an electrolyzer from a storage tank containing water from CO<sub>2</sub> reduction.

### Solid Polymer Water Electrolysis (SPWE)

A solid plastic membrane of perfluorinated sulfonic acid polymer (~ 0.30 mm thick) becomes an electrolyte when saturated with water. Catalyzed electrodes (better power efficiency) are in intimate contact with both sides of the membrane. H<sub>2</sub> gas is separated from the water feed by an external dynamic 0g phase separator pump.

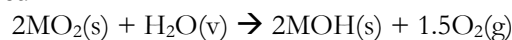
### Carbon Dioxide Electrolysis (CDE)

This electrolysis uses a solid oxide electrolyte with both sides coated with a porous metal catalyst-electrode, e.g. Pt. CO<sub>2</sub> direct from a CO<sub>2</sub> concentrator is electrolyzed to O<sub>2</sub>. Solid C deposits on a reactor catalyst; CO<sub>2</sub> formed is recycled to the electrolysis cell.

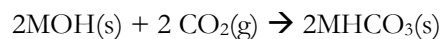
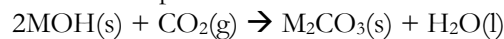
### Superoxides

The following describes the process of O<sub>2</sub> generation by superoxides (Center, 1988):

Stored O<sub>2</sub> is released:



CO<sub>2</sub> is removed from the atmosphere:



## *Biological Life Support Systems (BLSS)*

Biological life support systems rely on bioregenerative processes to close the air, water, food and waste recycling loops. Unlike physico-chemical processes, for which specific gas recycling processes can be isolated or segregated, biological systems integrate carbon dioxide assimilation, carbon dioxide reduction and oxygen generation along with other bioregenerative processes for food production and waste treatment. Photosynthetic organisms, such as plants or algae, constitute major components of BLSS, producing food, oxygen, and potable water, and removing carbon dioxide exhaled by the crew. Physico-chemical subsystems will be required to support these biological functions, including temperature and humidity control hardware, a food processing system to convert biomass into edible food, and a waste processing system to convert waste products, including waste water, into useful resources. A BLSS provides a much more Earth-like environment than physico-chemical systems, and produces fresh fruit and vegetables, lending more variety and palatability to the crew's diet (Gugliotta, 2006).

## Higher Plants

Plants can also reduce carbon dioxide, converting it to edible biomass through photosynthesis. The inputs of plant growth systems are light energy, carbon dioxide, water and nutrients. The outputs are biomass, oxygen, heat and water. The range of requirements with respect to input and output values is quite large depending on the concept and technology chosen. The choice of plants to be grown at a certain phase will have to be matched carefully with the equipment and experience available in a given time frame (Koelle, 2000).

## Algae

Algae, like plants, have the ability to perform photosynthesis, assimilating carbon dioxide and releasing oxygen. Their simple unicellular structure enables them to convert light energy into biomass at efficiencies greater than those of higher plants. They confer a number of advantages with respect to BLSS atmosphere regeneration (and food production): rapid growth, controllable metabolism, high harvest index, greater solar utilization efficiencies (~5%) compared to typical terrestrial plants (~0.2%) and high carbon dioxide resistance (Jones, 2006a). There are two categories of candidates suitable for a lunar BLSS:

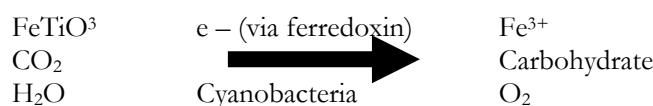
- Green algae (chlorophyta) – Chlorella (several species) and Scenedesmus
- Blue-green algae/cyanobacteria (cyanophyta) – Spirulina and Anacystis

Chlorella and Spirulina are the most promising candidates and the bulk of studies on algae in BLSS have focused on these two species (Eckart, 1994).

Cyanobacteria Spirulina has been shown in studies to offer much increased photosynthetic ability. Furthermore, due to their micro-algae scale they use less of the byproduct nutrients in their own growth. This offers great opportunities for using Spirulina as a highly nutritious, vitamin and mineral rich food source. Benefits of using this strain are an increase in anti-oxidant defense, more detail for which can be found in the Ohio/JSC paper (Bayless et al., 2006).

Further still, Spirulina was shown recently to have the highest level of O<sub>2</sub> evolution (photosystem II activity) for any oxygenic organism (Ananyev and Dismukes, 2005).

Work at Ohio University and Johnson Spaceflight Center, focused on using Spirulina (*Spirulina Arthrospira platensis*) in membrane photoreactors, optic fiber fed light from a tracking solar collector on a summer day at a rate of about 500 W m<sup>2</sup> average solar flux. A 40 litre batch reactor was used to cultivate the sample which was added to a membrane photo reactor of 80 m<sup>2</sup>, 20 2x2m membranes 10 cm apart with a total volume of 70 litres of water (2.5 litres of water per membrane). This work was able to operate at 3.5 kg (recommended per person per day value) of O<sub>2</sub> per 2.7 kg of Spirulina, which equates to 48 m<sup>2</sup> of bioreactor film per person or 576 m<sup>2</sup> for the crew of 11+1. The Cyanobacteria can use lunar regolith as a mineral source, tying in with ISRU usage, photosynthesis with Ilmenite produces Fe<sup>3+</sup> which can be electrolyzed out to retrieve Iron or as a mineral resource for higher plants or a great iron rich source for the crew. The chemical processes that describe these reactions to extract metal and oxygen from regolith are seen below.



### 3.2.5 Water Methods

Water methods could be divided in two different philosophies. Methods, usually used in open loop systems, create water through chemical reactions. The other methods try to obtain water through cleaning processes either physico-chemical or bioregenerative.

#### Re-supply

Water is provided via re-supply in the early stages of constructing the lunar habitat. Re-supplied water is stored in long term storage tanks. Note that these tanks should have bacteria termination systems. The obvious disadvantage of this method is that it requires a continuous re-supply. There is a possibility of re-supplying water from processing of regolith or from the by-product of fuel cells which is ultra-pure water, both of which can be stored in tanks as well.

#### Physico-Chemical

In the lunar habitat, water is evaporated through normal environmental processes. Therefore, a water condensation system for evaporated water is required. The system would also be used for recovery of water from urine. This water is then used for O<sub>2</sub> generation or as re-cycled potable water. To obtain water from urine, it is centrifuged, evaporated at low pressure and then condensed on the opposite side of the surface. The problem is that 5% of the water is lost in this system. Any remaining organic contaminants and microorganisms are removed by a high-temperature catalytic reactor assembly.

**Sabatier process:** Oxygen is produced by the electrolysis of water. Some of hydrogen, which comes from the electrolysis, can be recombined with carbon dioxide to obtain water and methane. The hydrogen that is not needed and the methane are vented externally.  $\text{CO}_2 + 4\text{H}_2 \rightarrow 2\text{H}_2\text{O} + \text{CH}_4$

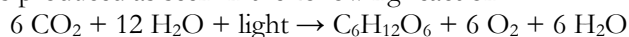
#### Filtration

Waste water is multi-filtered through membrane technologies which are well known and developed so far. Then, the filtered water is usually partially oxidized and ion exchanged.

The Vapor Phase Catalytic Ammonia Removal (VPCAR) system: This is a highly integrated unit that processes a combined wastewater stream to produce potable water. Distillation of the wastewater occurs in the wiped film rotating disks (WFRD) to remove many inorganic contaminants. The distillate is treated in oxidation and reduction reactors to oxidize lightweight organic components and ammonia and reduce any oxidized nitrogen compounds such as N<sub>2</sub>O to nitrogen gas. The design is highly thermally integrated and all components designed to be packaged in an ISS-like rack configuration. This system is believed to achieve 98% water recovery.

Bio-regenerative: Micro-algae, fungi, and yeast or higher plants are used for water regeneration. A bioregenerative system uses biological reactors to oxidize organic compounds and convert ammonia to nitrogen. Waste water flows into plant fields and is absorbed by algae. Transpired water is then condensed by air conditioners, phytotron moisture condensers, and then a drying chamber, and finally an incinerator is used for the burning of inedible biomass so to obtain purified water. A post-processing system uses ion exchange beds to remove any remaining inorganic contaminants and photo-oxidation to destroy any remaining organic contaminants. This system achieves 98% water recovery. Water is then consumed by plants as they perform photosynthesis to produce sugars, and at the same time

plants also transpire water. Photosynthesis is a process where water is destroyed and glucose is produced as seen in the following reaction:



Sugars evolve into the structure of the plant, and when herbivores consume plants, these components pass to these consumers. Later, higher animals burn these sugars for energy, and water is produced again in the process, closing the water loop.

### 3.2.6 Food Methods

There several different methods for supplying the crew with food these are complete re-supply, food production and various levels of combination of these two.

#### *Re-supply*

Re-supply involves sending all the necessary food at required intervals. Re-supplied food is stored on-board the space craft in dehydrated or sterilized form to prevent the food from spoiling. The food can later be hydrated using water. The re-supply of food requires a multiple launches increasing the long term costs of the lunar habitat. Additionally, for long duration missions such as those proposed for Luna Gaia, large areas for food storage and packaging waste would be required.

#### *Food production*

There are several different methods that can be used for food production. Those most beneficial are the ones that can be performed in confined spaces and without the need for a large amount of resources. Additional methods in oxygen generation or waste processing are required to assist in closing the loops to the maximum potential. The methods for food production include algal, plants, insects and animal systems.

Algal systems which have application for utilization in the life support can be grouped into two areas; green algae (Chlorophyta) and blue-green algae (Cyanophyta). These types of algae have several advantages as they have a rapid growth rate, are able to produce oxygen and selection of certain algal types can be useful for harvesting and ingestion by the crew. Spirulina and Chlorella are two examples of algae which can be both utilized as an oxygen generator and food source. The problems with algal systems as a food source include the acceptability of the crew to eat algae and processing of algae. However it is possible to utilize the algae as a fertilizer or food source for plants and animals respectively (Eckart, 1994) (Eckart, 1999).

Higher plants also have multiple advantages for being used as a food source because by correct selection, variety and growth medium a large majority of the crew's nutritional requirements can be achieved (Eckart, 1999), Wheeler et al., 2003). Plants are able to supply calories, proteins, fats, carbohydrates, minerals, vitamins and trace elements. The plants also contribute to the generation of oxygen and can be utilized for water purification through the collection of vapor produced. The disadvantage of plants is that not all of the biomass produced is edible and they also require large amounts of space and resources namely, water and energy in the form of light to perform the functions. The inedible biomass could be recycled to provide fertilizer, building material or in the case of foliage as a food source for animals (Eckart, 1994, Eckart, 1996a).

The use of insects as a food source on the Moon is another possibility. Insects are rich in animal protein and consequently they would provide an efficient means for obtaining animal protein (Eckart, 1999). Some possible candidates would be silkworm, hawk moth, drugstore beetle and termite. Byproducts such as silk fiber could possibly be used to weave cloth, and feces could be utilized as fertilizing soil for plants or for animal production such as fish (Nakayama and al.).

Animals are an additional source of food for the crew. They can provide additional variety and nutrition to a diet. Animals however increase the system complexity and size. Previous studies have shown that considerations must be given to the energy, mass and the required volume of the system. However, some animals were identified as conferring stability to the system, especially animals with low mass and short gestation periods enabling quick replacement and replenishment within the system (Eckart, 1999).

### Nutritional Supplements

The use of nutritional supplements can be provided to astronauts to account for nutritional requirements which are not supplied to the astronaut by the food provided. Although every attempt is made to provide all the necessary nutrients the limited food supply does not always provide all the requirements. In the case of food re-supply the storage methods often mitigate some of the vitamins or minerals that would normally be provided by the un-preserved version of the food. In the case of local food production the limited amount of food types and variety that is produced does not always allow for all requirements to be provided. Consequently nutritional supplements can be provided to the crew to ensure that receive. However these supplements are difficult to produce locally and therefore a required to be re-supplied and stored.

### *Waste Treatment*

There are many different methodologies in dealing with waste these include storage, disposal, incineration and biological degradation. The type of method utilized depends on the waste. The aim of Luna Gaia is to achieve a high percentage of closed loop and therefore it is most likely that products which can not be easily recycled will not be used. There are of course exceptions such as medical or nuclear waste which must be dealt with carefully.

The storage of waste could be achieved and then brought back to Earth for processing when the crews are rotated. However returning the waste to the Earth is costly due to the large amount of transportation. This option would allow for the minimal amount of infrastructure on the lunar surface but would require a larger transportation system to carry the waste to Earth such a system could become prohibitively expensive. This option also does not provide for a significant achievement in closing the loop. An extension of the storage method which also does not attempt to close the loop is the disposal method. These systems are often referred to as open loop systems. An example of the use of these methods is on the ISS where water is utilized to generate oxygen and the potentially useful hydrogen is vented overboard.

Another ISS example is where waste is stored in Progress capsules until they re-enter the Earth's atmosphere and are incinerated. Incineration was utilized in Bios-3 in a closed loop manner where inedible plant material and waste was burnt at very high temperatures to produce CO<sub>2</sub> which was then pumped back in the growth chambers to assist in plant growth (Eckart, 1994).

In addition to solid waste produced by humans, the organic waste in life support systems that are based on higher plants come mainly from the higher plants



themselves. Vegetables are composed of three parts: an edible part subdivided into a digestible part and a dietary fiber part, and an inedible part. Inedible biomass, consisting of roots, leaves and stems is a byproduct of growing higher plants. A closure for the system could be reached only if the problem of inedible biomass is solved. There are two possible paths for recycling waste produced by the plants: the destruction of organic substances by either aerobic or anaerobic processes.

Anaerobic processes require little energy, but produce liquid and gaseous substances that require further degradation or utilization, including methane, hydrogen and organic acids. Aerobic processes give more readily available products but require oxygen supply through aeration.

Degradation of cellulose and lignin from higher plant has been studied in Bios-3 and the FoOD project (Fungus on Orbit Demonstration). Higher fungi appeared to be a promising method allowing for the mineralization of the inedible parts, as well as providing a food source for the crew (Cristina et al., 2000) (ESA, 2001).

### 3.2.7 Previous Closed Loop Life Support System Efforts

Test beds have been previously investigated in order to develop and perform research on closed environmental life support systems (CELSS). These have ranged from small 100ml flasks up to large biospheres that mimic the Earth's biosphere (Eckart, 1994). Important for this study are those including humans and designed for space based applications. Table 3.2-5 gives percentages of achieved self-sustainability and the following section discuss these systems.

**Table 3.2-5 Degree of Achievement of Self-Sustainability**

	Atmosphere	Water	Food	Waste
<b>MIR/ISS</b>	0%*	>0%*	0%***	0%*
<b>Biosphere II</b>	100%**	100%**	100%**	Unknown
<b>BIOS-3</b>	100%*	100%*	70-80%*	Unknown
<b>MELISSA</b>	100%****	92.4%****	Unknown	70%****

\* Eckart, 1996

\*\*\*Wieland, 1994

\*\* Eckart, 1994

\*\*\*\*NASA, 2006

#### *Mir and ISS*

The Russian Mir used and the Russian segment of ISS uses a Vozdukh system to remove carbon dioxide and vent it overboard. An Elektron oxygen generator uses electrolysis to produce oxygen from water, but the hydrogen is vented. The US segment utilizes an Oxygen Generation System (OGS) rack based on submarine technology and is scheduled for the addition of a Sabatier Carbon Dioxide Reduction Assembly. The food and water is entirely re-supplied via NASA's space shuttle orbiter and Russian Progress modules.

#### *Biosphere 2*

Biosphere 2 simulated the Earth biosphere to support eight individuals closing the water, air and food cycles completely. This required a large enclosed biosphere of 180,000 m<sup>3</sup> with tropical, marsh, desert, ocean and agricultural areas utilizing soil as the growth medium (Eckart, 1994).

Biosphere 2 used a system of fans to circulate air and to bring it in contact with the greenhouse section for natural processing (Institute). Some outgassing compounds in Biosphere 2 coming from materials, equipment, living plants, animals, soils or from people were in the air. To solve this problem in Biosphere

2 was developed a “soil bed reactor” technology. These soil bed forced air through the microbial communities of the soil and these microbes through their metabolism destroyed the trace gases (Eckart, 1994).

The water cycled from the salt water “ocean” to the fresh “rain” systems, to the streams and marsh and back to the ocean. In this cycle, the potable water for the inhabitants is obtained by condensation of the water and processed via a two-stage filtration and UV-sterilization process. The waste products from both the humans and domestic animals were initially decomposed in anaerobic holding tanks. Batch treatment then occurs in aerobic “marsh” lagoons which circulate the water, exposing it to the water plants which continue the regeneration process. After passing through the marsh waste water system, the water is added to the irrigation supply for the agricultural crops (Zabel et al., 1999).

The diets were mainly vegetarian consisting of a wide variety of fruits, vegetables and cereals combined with small amounts of goat milk, yogurt, goat meat, pork, chicken, fish and eggs. The sun was utilized as a light source with only trace amounts of UV passing through the enclosure. The crop productivity was greater than conventional Earth based agriculture due to the higher amount of climate control, crop selection, nutrient recycling and increased CO<sub>2</sub> levels. The diet was sufficient to provide all required nutrients except for vitamins D, B<sub>12</sub> and calcium. Supplements consisting of 50% of the daily vitamin and mineral requirements were also provided to the inhabitants (Eckart, 1994) (Marino et al., 1999).

### *Bios-3*

Bios 1, 2 and 3 were Soviet/ Russian closed loop systems. Bios-3 was designed to support a crew of 2-3 in a closed loop life support system consisting of 4 compartments. Air was produced by utilizing *Chlorella* and higher plants for photosynthesis recycling CO<sub>2</sub> exhaled by the crew. A thermo catalytic filter was employed to eliminate the excess organic gaseous emissions. Potable water was obtained by purification using activated charcoal, ion-exchange and boiling. Urine was added to the plants as a fertilizer. Biomass and kitchen wastes were dried and stored. The food grown hydroponically was able to provide 70% of the calorific requirements. Light was provided by high irradiance artificial light and the climate controlled at 70% relative humidity with a temperature of 22-24°C. Bios-3 incinerated inedible biomass at a high temperature to ensure no CO was produced and fed the produced CO<sub>2</sub> back to the phytrons. To supplement the food produced beef, pork, poultry and fish was introduced once a month (Eckart, 1994).

### *MELiSSA*

MELiSSA (Micro-Ecological Life Support System Alternative) has been conceived as a micro-organisms and higher plants based ecosystem. The driving element of MELiSSA is the recovery of waste, carbon dioxide and minerals, using light as source of energy to promote biological photosynthesis. The MELiSSA cycle diagram for air, water and waste is shown in Figure 3.2-6 (ESA, 2006).

### *NASA Efforts*

The Johnson Space Center Closed Loop test chamber used molecular sieve to remove carbon dioxide and a Sabatier processor to generate methane and water during four tests between 1995 and 1997. Oxygen was generated by electrolysis and air contaminants removed by charcoal/filter bed. Further tests used solid

waste incinerators to generate carbon dioxide and grew wheat and lettuce to assist in the generation of oxygen and food and the removal of carbon dioxide.

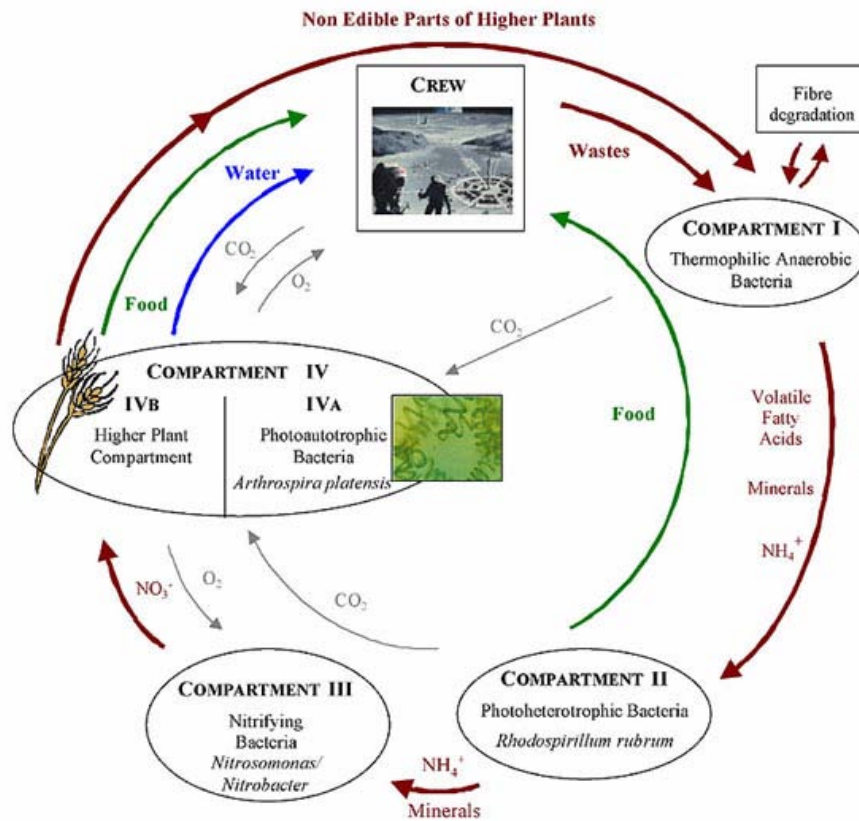


Figure 3.2-6 The MELiSSA cycle diagram

The IWRS (Integrated Water Recovery System) processes a combined wastewater stream. It uses biological reactors to oxidize organic compounds and convert ammonia to nitrogen. A reverse osmosis (RO) system treats the BWP (Biological Water Processor) effluent and is the primary inorganic removal system. The RO system produces concentrated brine that is processed by the Air Evaporation System (AES). In the AES, a wick absorbs the brine and a hot air stream evaporates the water out while the contaminants accumulate in the wick. That water is condensed from the air stream and combined with the RO permeate to be polished by the Post-Processing System (PPS). The PPS uses ion exchange beds to remove any remaining inorganic contaminants and photo-oxidation to destroy any remaining organic contaminants. The IWRS system achieved 98% water recovery.

The NASA Kennedy Space Center looked at plant production within the Breadboard Project. Experiments looked at crop production and effect that periods of light and light levels have on different crops including wheat, soybean, lettuce and potatoes utilizing nutrient film as the growing medium (Eckart, 1999).

### Antarctic Concordia Station

This station has a water closed loop system based on MELiSSA. The Antarctic environment is protected by international treaties, and all waste materials must be removed from the Continent, making wastewater treatment a major issue. To only partially recycle the water and not all the wastes, not all of the four compartments of MELiSSA are needed. In Concordia Station there's a hybrid system between the biological MELiSSA system and a physical-chemical method.

Only using the first and third compartment, the black water coming from the toilet, is converted to grey water. Grey water is analog to the quality of water coming from the shower. To make the grey water become hygienic water, it is processed by an artificial process based on multi-filtration membrane and reverse osmosis (Sadler, 2006).

On the Concordia Station, they grow mostly salad crops, lettuce, spinach, tomatoes, cucumbers, strawberries and recently just grew the first cantaloupes at the South Pole. Additionally, they grow herbs for cooking and nasturtiums as edible flowers (Sadler, 2006).

### *Closed Equilibrated Biological Aquatic System (CEBAS)*

CEBAS is a small experiment facility that has been tested aboard the ISS to study an artificial ecosystem. CEBAS follows a three components philosophy in which a zoological component (a space aquarium for aquatic animal), the botanical component (higher-water-plant cultivator), the microbial component (filter with special bacteria oxidizing the ammonium excreted by the animals to NO<sub>2</sub><sup>-</sup> and NO<sub>3</sub><sup>-</sup>) are integrated by a control unit.

### **3.2.8 Recommended Solution: Luna Gaia Life Support System (LuGaLiSuS)**

A bioregenerative life support system was selected for Luna Gaia. A Lockheed report previously showed that depending on the size of the crew the breakeven point between using re-supply and a closed loop system could be between 2.4 and 2.8 years. For long term missions of 18 months to 3 years it is therefore necessary to utilize a regenerative life support system. Re-supply technologies are already at a competent level or readiness and to further technologies as a first step to Mars exploration closed loop life support is necessary.

Luna Gaia Life Support System (LuGaLiSuS) is an extension of research previously performed on closed loop life support systems with emphasis on two past experimental closed loop projects that produced successful results.

The two baseline systems were Bios-3 and MELiSSA. The Soviet/Russian Bios systems had a proven track record with experiments and developments of the system beginning in the mid 1960's and continuing for a period of 20 years. The Bios-3 system was very successful in closing the air and water loops but not at recycling wastes and satisfying all the food requirements. The MELiSSA utilizes an improved biological waste recycling system combined with cyanobacteria and higher plants to produce the necessary food requirements of the crew.

These systems were combined and improved upon with the research obtained from other projects such as the Advanced Life Support (ALS) Studies at the NASA Johnson Space Center and Closed Equilibrated Biological Aquatic System (CEBAS).

In attempting to solve the waste recycling problem LuGaLiSuS is a hybrid system incorporating biological and physico-chemical methods combining Bios-3 with MELiSSA and utilizing physico-chemical methods for redundancy. During the initial phases the physico-chemical systems are utilized until the bio-regenerative approach is fully established. However, some physico-chemical processes are still required for trace contaminant control and final water purification.

LuGaLiSuS combines both systems in an optimum way and removes parts of MELiSSA and Bios 3 that have similar utilities. For example, MELiSSA uses a

type of cyanobacteria (*Arthrospira platensis*) to regenerate oxygen, but Bios 3 uses chlorella. Cyanobacteria was chosen as a primary solution because it has better results than its predecessors. However, chlorella is not totally removed from the system because it is considered a robust and still very efficient solution. Future study is required to see if both bacteria can live together.

### *LuGaLiSuS Systems*

The complexity of LuGaLiSuS is apparent in Figure 3.2-7. There are numerous sub-systems with several having multiple functions. The crew compartment takes in the food, water and oxygen required in order for the survival of the crew. The waste from the crew compartment is separated into water vapor, grey water containing urine, and black water containing feces and other waste. The water vapor is fed back to the water vapor condensers which return it to liquid water and assist in controlling humidity.

The water vapor condensers are also connected to the algal cultivator, plant growth chambers and aquaculture chamber to recover evaporated water. This water is relatively clean as the algae, plants and aquaculture remove harmful contaminants. The water vapor condensers work by using a porous stainless steel plate cooled below dew point temperature and attached to a pump creating negative pressure. Water vapor is condensed on the plate and suctioned to be returned to the water loop. Water is then further purified by active charcoal bed filters, reverse osmosis and UV treatment. Water is now potable and is stored in a water holding tank.

Certain extremophile bacteria have been shown to liberate oxygen from mineral ores, leaving nodules or solutions of the element metals behind. These ions may be recovered from the solution. This offers a biological way to generate oxygen and hydrogen from the lunar regolith. Current research focuses on mutated strains of cyanobacteria (CB) but the concept of splicing genes from extremophile bacteria into *Escherichia coli* presents another possibility that can be explored (Bayless et al., 2006) (Canada, 2006).

### *Grey water treatment*

Grey water comes from the urinal, the shower and from other hygienic needs like washing dishes and clothes. This water is not severely contaminated and it has a lower percentage of contaminants when compared to black water but its processing is more complex than that of evaporated water. The first stage is an Ion Exchange Bed that eliminates high mineral content from the crew urine. It is then channeled into the algal cultivator compartment. This compartment houses several types of micro-algae, including *Spirulina* and chlorella and serves to process, purify and filter the water very efficiently by transpiration of the water into vapor.

Additionally the algal cultivator compartment recycles the atmosphere by taking carbon dioxide exhaled by the crew and producing oxygen. The algae are a feeding source for the aquaculture chamber and also for the crew. The Bios-3 experiment showed that the diet of the crew could be supplemented with 20% algal content (Eckart, 1994). The water and oxygen from algal chamber is then passed to the plant and aquaculture chamber.

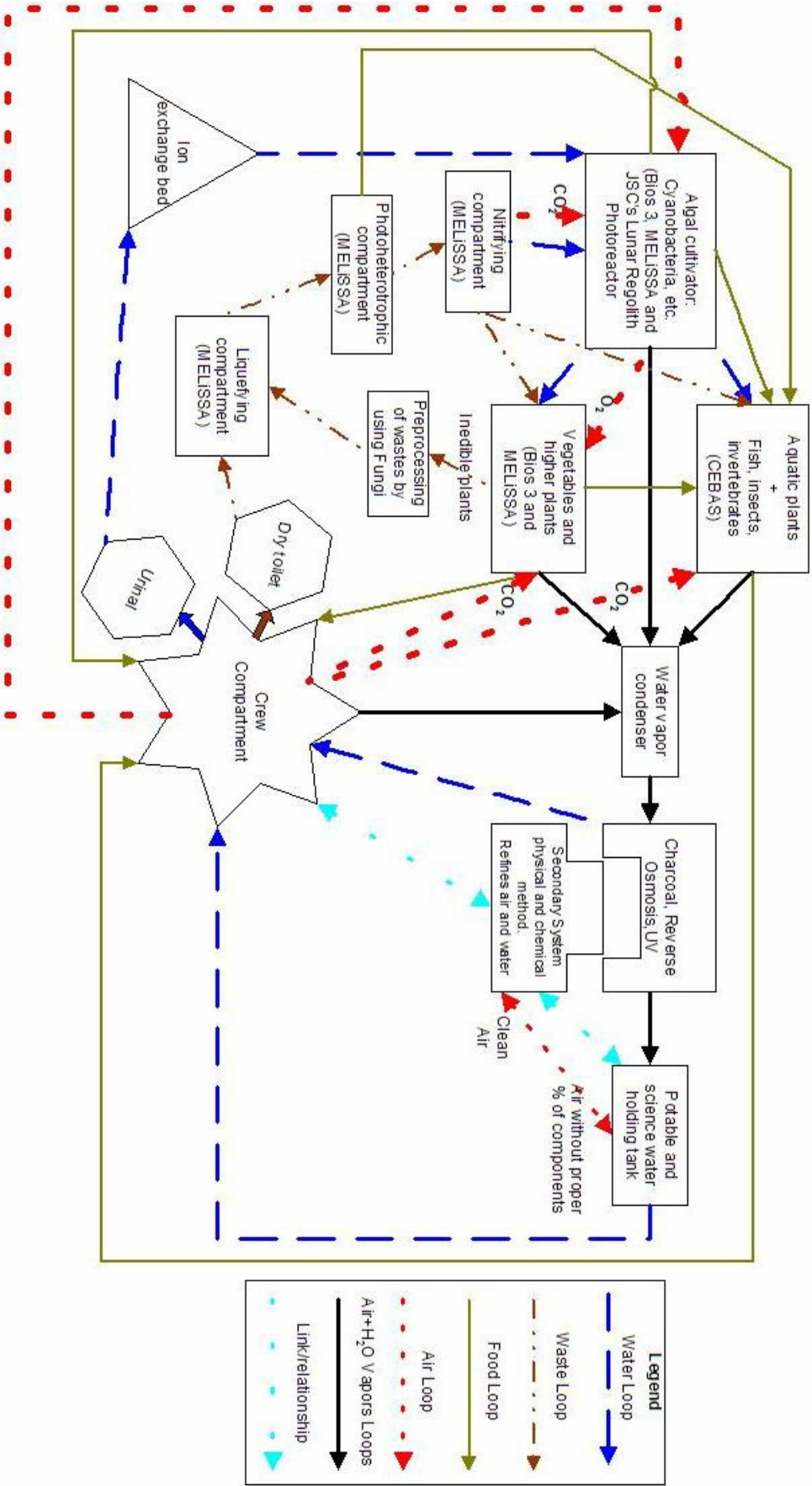


Figure 3.2-7 LuGaLiSus System Block Diagram

The next compartments are the plant and the aquaculture compartments. These compartments contain most of the water in LuGaLiSuS that is not in the water holding tank. All these plants have strong water needs and aquatic plants require even more.

*Food requirements*

The use of only algae as a food source could lead to several medical symptoms, including dyspeptic phenomena, belching, nausea and appetite loss (Eckart, 1994). The plant compartment provides the major additional source of food for the crew. The plant types and daily diet is given Table 3.2-6a (Swartzkopf et al., 1991) and listed as a percentage of the recommended daily intake in Table 3.2-6b (Swartzkopf et al., 1991). Previous studies have suggested that 20 m<sup>2</sup>/person would be an adequate growth area to supply the crew (Eckart, 1999). Ideally plants would have short stalks to save room, would have few inedible parts, would grow well in low light, and would be resistant to microbial disease. Research is underway at KSC to choose varieties of wheat, rice, lettuce, potatoes and other plants that meet these criteria (Wheeler et al., 2003).

**Table 3.2-6a: Proposed Daily Crew Diet**

Food	Daily portion [grams]
Soybeans	100
Peanut	100
Wheat	400
Carrots	300
Lettuce	200
Tomato	200
Tilapia	50

**Table 3.2-6b: Nutritional requirements**

Nutritional Characteristic	USDA Recommended Daily Amount	% of Recommend Daily Amount
Energy (Calories)	2700	94.6
Protein (gm)	56	222.3
Fat (gm)	90	86.2
Carbohydrate (gm)	392	98.1
Calcium (mg)	800	120.6
Phosphorus (mg)	800	364.6
Iron (mg)	14	219.9
Sodium (mg)	220	85
Potassium (mg)	3050	200.4
Vitamin A (IU)	1000	571.3
Thiamine (mg)	1.4	342.9
Riboflavin (mg)	1.6	81.9
Niacin (mg)	18	227.8
Ascorbic Acid (mg)	60	176.7

The aquaculture system also produces a food product: tilapia fish. Fish is one of the most efficient animal products based on feed conversion efficiency and harvest index. Here, we propose to incorporate aquaculture system into LuGaLiSuS (Eckart, 1994). The fundamental basis for the aquaculture system is the work performed on CEBAS. Since we use the microbial compartment of the MELiSSA system for decomposing human waste and inedible parts of plants in LuGaLiSuS,

the microbial component in CEBAS will be integrated into the MELiSSA decomposing system. The decomposed materials from waste management loop feed aquatic plants and fish. There are several advantages to using a CEBAS system. First is that the aquatic chamber can become the preliminary system for production of water vapor in case of enhanced and diminished growth of plant life making the system. Another reason is that photosynthesis was maintained simply by switching plant chamber illumination on and off. The CEBAS systems are also located in the living sections of the habitat which can provide a soothing view for the crew. The aquatic chamber can also produce *Ceratophyllum demersum* – a rootless non-gravitropic edible water plant, and water snails *Biomphalaria glabrata* (Scwartzkopf et al., 1991).

### *Black water treatment*

The treatment of black water uses the MELiSSA system as a basis. This is the waste coming from the toilet and also the water contained in food wastes and human feces. The MELiSSA system's first three stages are to transform black water into grey water and wastes into useful chemical products for plants.

The first compartment is the Liquefying Compartment. This compartment anaerobically transforms the waste into hydrogen, carbon dioxide, volatile fatty acids, minerals and water. The organisms in this compartment include proteolytic bacteria. The liquefying compartment is also fed by the preprocessing compartment which takes inedible biomass and breaks it down using higher fungi. Higher fungi is a promising approach for the mineralization of inedible plant parts, especially for the problems encountered with the degradation of polymerized compound like cellulose and lignin (Marino et al., 1999).

All these outputs go the Photoheterotrophic Compartment. This compartment is populated by *Rhodospirillum rubrum* bacteria which are responsible for eliminating terminal products. The outputs of this biochemical process lead to water, mineral and  $\text{NH}_4$ . The *Rhodospirillum rubrum* bacteria can also be utilized as a food source for the aquaculture system (ESA, 2006).

The Nitrifying Compartment converts ammonium ( $\text{NH}_4^+$ ) derived from biological waste into nitrate ( $\text{NO}_3^-$ ), the preferred nitrogen source for plants and *Arthrospira platensis*. The MELiSSA nitrifying compartment is a fixed bed reactor colonized by *Nitrosomas* and *Nitrobacter* which oxidize  $\text{NH}_4^+$  to  $\text{NO}_2^-$  and  $\text{NO}_2^-$  to  $\text{NO}_3^-$  respectively. The nitrifying species receive oxygen from the plant compartment and release carbon dioxide to the algae compartment. After these waste compartments, the water is put into the algal cultivator and it subsequently follows the same cycle of the grey water emanating from the crew compartment (Eckart, 1996a).

### *Other issues*

Another important issue is the pureness of the water. After the filtration stage for the water, many 'good' microorganisms are removed and consequently possible benefits of the water are lost. During the Bios-3 experiments after purification of the water small quantities of salts, KI and KCl were added for taste and nutritional benefits (Eckart, 1994).

One of the problems in this biosphere may arise from low levels of  $\text{CO}_2$ , since everything aims to provide oxygen and remove  $\text{CO}_2$ . To make the primary system more robust, a tank containing  $\text{CO}_2$  may have to be added to the biosphere to provide for the plants.



## Summary

Although every effort has been made to close the air, water, food and waste loops there are still other loops that should be considered which are outside the scope of this project. An example of these loops is the mineral loop which within this report is assumed to be completed by the mineral and nutritional supplements. There are also other possibilities where the plants could produce ethylene which would have to be removed by oxidizer filters such as titanium oxide. Mineral tablets can be stored and re-supplied after some years. The LuGaLiSuS system cannot be said to be 100% closed.

Utilizing Figure 3.2-7 it can be seen that a closed loop percentage of 90-95% can be expected for Luna-Gaia. The food and waste cycles are almost completely closed with some systems requiring spares and nutritional supplements required for the crew. It is also expected that not all waste can be recycled since there is no provision for non-biodegradable products.

### 3.2.9 Redundancy

A secondary closed loop life support system must be ready to start working if the primary system of LuGaLiSuS fails. This means that it must be prepared to work irregularly. The secondary system will function as the primary system while the biosphere is being developed and cannot yet start producing and recycling the basic products.

This secondary system must provide a reliable technology that it is not based on biological processes; in other words a system with a different engineering philosophy. Because of this the secondary system is based on physical and chemical methods. It is not so important to close the loop in a perfect manner because this system does not aim to provide food, oxygen and water for three years.

This secondary system must provide a reliable technology that it is not based on biological processes; in other words a system with a different engineering philosophy. Because of this the secondary system is based on physical and chemical methods. It is not so important to close the loop in a perfect manner because this system does not aim to provide food, oxygen and water for three years. Figure 3.2-8 shows resupply mass requirements to maintain the closed loop systems (Tolyarenko, 2006).

### 3.2.10 Physico-Chemical Back-Up Systems

This section outlines the physico-chemical back-up systems implemented in LuGaLiSuS.

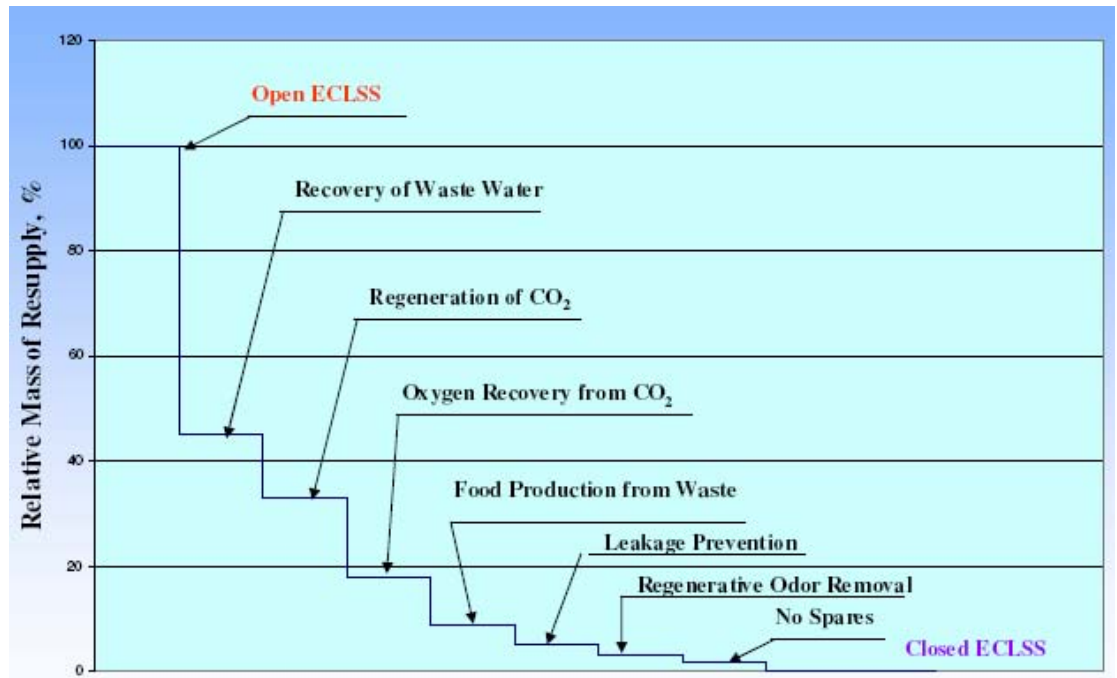
#### *Carbon Dioxide Removal – Four-Bed Molecular Sieve (with Electrochemical Depolarized Concentrator as Back-Up)*

The recommended physico-chemical back-up system for carbon dioxide removal is the 4BMS, with the EDC as a redundant system as there is hydrogen on the Moon and the EDC can directly connect to a Sabatier reactor. The 2BMS is the best method of carbon dioxide removal but more research is needed (Kanghan, 1995).

#### *Carbon Dioxide Reduction – Advanced Carbon Dioxide Reduction System (with Water Electrolysis)*

The carbon dioxide produced by the crew would initially be concentrated using a 4BMS or 2BMS. Initially (during the first year) a carbon dioxide reduction ASCR

and a water electrolysis unit sized for the initial crew would be used. These two subsystems would require about 200 kg of equipment per crew member, 60 kg of expendables per person per year, about 1.5 kW per person and a volume of 1.2 m<sup>3</sup> per person. Safety margins and requirements for structural components, plumbing, wiring and the inner and outer shell would have to be added. This would double or even triple the mass requirements. During this stage of the mission, the physico-chemical elements of the ARS would independently provide for all air revitalization functions. This would set free the oxygen, amounting to about 1/3 of the input mass (carbon dioxide), which would be returned to the habitat for consumption. The residuals (carbon or methane) would either be waste or would be processed at a later time employing an algae-reactor (Koelle, 2000).



**Figure 3.2-8 Re-supply Mass Required for Level of Closed Loop Systems**

#### *Oxygen Regeneration – Static Feed Water Electrolysis*

The recommended physico-chemical subsystem for oxygen generation is SFWE, based on the many advantages it offers: multiple uses for energy storage; ability to be linked to a water vapor electrolysis dehumidifier module for the removal of water vapor from effluent oxygen, thereby generating additional oxygen while eliminating the need for a water vapor/oxygen separator; ability to operate continuously or cyclically; ability to operate at high pressures (~68atm). These characteristics of the SFWE make it a more flexible system which can be adapted to a wider range of conditions that may be present on a lunar ECLSS (Center, 1988).

The ARS and the water management system would be activated with priority and gradually achieve near closure with a few percentage losses during the first operational year. The air would be dried by heat exchangers and the condensate would be regenerated as potable water. The carbon dioxide produced by the crew would be initially concentrated using a 4BMS or 2BMS. Initially (the first year) a carbon dioxide reduction ASCR and a water electrolysis unit sized for the initial crew would be used (Koelle, 2000).

In the second stage of the mission, in which the biomass production chambers would be activated, the physico-chemical elements would provide decreasing amounts of life support as higher plants would begin to provide increasing levels of air revitalization. Achieving carbon dioxide levels of less than 0.5 percent using physico-chemical technologies would become increasingly difficult because the removal efficiency typically decreases as carbon dioxide levels decrease. The potential role of plants in the removal of carbon dioxide is important. During metabolic step changes, the physico-chemical elements would automatically activate to compensate for the additional metabolic load (Koelle, 2000).

### *Location Specific Benefits*

- The base location was chosen to make use of two essential features. Namely, North Pole peaks have the greatest solar flux. The chosen crater has a bottom which is eternally dark and this sets up a temperature gradient from which one can have a natural convection current for air flow. This enables natural flow of CO<sub>2</sub> rich air from the crew compartment through to the greenhouse and O<sub>2</sub> rich air back to the crew habitation.
- Placing the base on a slope provides an incline from which reed bed filtration can be considered and the use of solar thermal sterilization of water using parabolic mirrors, which offers a way to drive clean water naturally back up to the crew habitation in the form of steam. It has been considered this offers benefits for energy production as a by-product. The inclination of the base also assists the air convection as the 1/6 g environment naturally hampers this process.
- As Section 2.3 describes, the heliostat mirrors used in the system are also used to thermally regulate the base. Mirrors shine solar radiation from the peaks of eternal light and this is the most efficient way to provide our higher plants and photoreactors with solar light.
- For more in depth discussion refer to Section 3.1 Design Architecture

### *Re-supply Requirements for the System*

Although the system works effectively for closing the air, water and waste loop the nutritional requirements are not fully met. Therefore the crew will require some form of nutritional supplements which can be provided in the logistics missions or when crew are rotated. The active charcoal beds will need to re-supplied over time. Other critical spare parts will have to be supplied to the base and pre-positioned over time, especially during the early stages where systems are being combined. High priority spare parts would include pumps, valves, pipe, fluid lines, circuitry, power regulation components and the parts required for the physico-chemical redundant system.

The pressure difference between the lunar habitat and the vacuum environment of the Moon has significant potential to cause atmospheric leakage. As the system loses atmospheric components to space, they need to be replaced via supply tanks that have either been transported from Earth or filled using gases generated through in-situ resource utilization processes. Biosphere 2, for example, experienced 10 % atmospheric leak rate per year. A sealing technique in Biosphere 2 included prevention of underground leaks by using a stainless steel liner in a tunnel encircling the foundation (Eckart, 1996b).

In order to minimize leakage, the wall material must be impermeable and hardware interfaces, such as hatches or windows, should be designed to minimize leakage. Using inflatable structures in the lunar habitat would diminish leakage since an

inflatable structure is no more vulnerable to puncture than a rigid one (Eckart, 1996b).

### 3.2.11 Recommendations for Research

The LuGaLiSuS closed loop life support system takes advantage of existing technology and previous research efforts in food processing, water purification, atmosphere regeneration and waste recycling. The novelty of the system is found in the integration of the most promising and efficient systems in order to succeed at providing a sustainable lunar habitat with minimal re-supply requirements. A careful testing of the appropriate integration of the different components is obviously mandatory to prove this system.

Few areas need to be further researched in order to make this project feasible. They mainly fall under contamination prevention, technology and food production. It should also be stated that we need to address thermal control of the base, though Section 3.1 Design Architecture does address this issue.

#### *Contamination Technologies and Prevention*

Important advances in contamination prevention technologies will need to be accomplished if a lunar laboratory is to be realized. Such technological advances could also contribute significantly to our ability to monitor and control pandemics and diseases on Earth, which will invariably become more pressing in the next decade. Improved technologies developed for Luna Gaia include the following:

- Cleaning (non-destructively and without residues) and validation techniques.
- Methods to mitigate contamination from biological organisms, or lunar regolith, may have influence on Earth based clean room technologies and biohazard protection.
- Maintenance of biologically clean work areas
- Research into this field improves microbiological containment procedures which have a bearing on hospitals and clinical research.
- Sterilization techniques for tools and containers.
- Compact and energy efficient methods of tool decontamination will result in cheaper ways to clean surgical tools.
- Encapsulation and containerization.
- Methods of preserving samples and protecting them from the human environment, and vice versa, will enable better containment and then safe storage of samples in less biologically secure locations.
- Advancements in seals for airlocks and containers.
- Mir showed that rubber seals could be attacked by mutant strains of bacteria. This will require research and development into materials to safeguard these important structures.
- Archival preservation of organic and inorganic samples.
- DNA preservation of species has been touted as a way to archive species both off planet in a DNA 'Library' but the same archive could be used to make copies for storage on Earth.
- Decontamination measures to destroy resistant microbes.
- Trace contaminant removal needs to be addressed, as certain trace contaminants built up in the Bios-3 system, without reaching critical levels.

Decontamination procedures research will be essential to maintain base hygiene and safety. The levels of contamination will have to be of a factor higher than

anything designed on Earth and so techniques to sterilize equipment and clothing will have to be developed. These will have major implications for containment of bioweapons or pathogens and perhaps a role in anti-bioterrorism.

### *Plant Crop Optimization*

#### Lighting Systems

Light plays a very important role for any plant. Lighting conditions, duration and wavelengths that help various crops to grow faster and healthier need to be determined. The lighting systems need to be optimized, so as to get information from sensors and act when hazard events occur by changing their parameters. For example, if not enough fruit is produced they will have to change the light to make crops grow faster. Or also if carbon dioxide or oxygen is not at suitable levels, light will have to be turned off or on. Lightweight lighting systems need to be developed, as the mass of these systems is critical to lower launch cost.

#### Growth Mediums

Different types of soil substitute need to be investigated. The best choice for each plant regarding the nutrients and minerals contents of the nutrient solution needs to be evaluated.

#### Algal Based Growth Solutions

The LuGaLiSuS regenerative system utilizes algae for atmosphere regeneration and food supply. More research is imperative to find if more efficient bacteria could replace chlorella and spirulina, the proposed strain for LuGaLiSuS. Additionally, bacteria are grown in simple tanks that may not be the optimum apparatus. To increase bacteria efficiency, more studies need to be done in the synergies between micro algae and other organisms.

#### Nutrient Enriched Algal Growth Beds

One of the solutions to improve algae efficiency is using special enriched beds. More studies need to be done to obtain the best nutrient enriched beds for each of the different algae.

### *Food Recommendations*

#### Insect Utilization

A normal diet needs to provide proteins. A good source of proteins for a closed loop life support system may be insects. They are small, very nutritious, and have low space and mass requirements for reproduction and growth. Insects are very resistant to hazardous events and all of their parts can be eaten. To be able to use insects successfully, research in what kind of plants and what kind of insects can coexist together and produce a stable habitat needs to be done.

#### Fish production

In order to improve the quality of the diet and crew morale in the lunar base is providing meat. The LuGaLiSuS system provides fish meat. Fish need to live in water tanks, which require a lot of volume and mass. However, they provide a good meat source compared to usual livestock which require even greater volume, mass and energy for the development. A selection of fish species should be done in order to obtain the one that can live in small volumes, are very nutritive and tasty, reproduce and grow fast and are very resistant to sub-optimal waters.

#### Supplements Storage and Re-supply

New ways of storing large amounts of food in very small volumes would be beneficial. In case something goes wrong in the food productivity of LuGaLiSuS,

enough food needs to be so that the crew can live while a rescue mission is accomplished. Drying the food is one of the solutions, but further studies can be done.

#### Inedible plant degradation

Fungi have been identified as a part of the waste degradation component. Further studies need to be done concerning the integration of fungi as a subsystem in artificial closed ecosystems.

#### *Linked Technologies – Extremophile Gene Splicing*

Using the same biotechnology used to produce Insulin on a commercial level, one can splice the DNA necessary to liberate oxygen from lunar or Martian regolith directly from the mineral ore, minus the need for a photo reactor. This means that a sample of bioengineered bacteria could be used to liberate oxygen for terraforming a planet, such as Mars, however, this uncontrolled reaction may well be deemed un-ethical. A controlling feature would have to be employed, and this may be installing the bioengineered bacteria with a dependency on an enzyme it can't create, again via gene splicing technology. This is better than relying on an antibiotic barrier around the reaction chamber or area, as mutation of bacteria towards antibiotic resistance, as evidenced on Earth, is more likely to happen than the mutation towards a whole gene able to produce the required protein/enzyme or amino acid. This is likely to take many thousands of generations of a single bacterial lineage, thus making the dependency on a bigger protein as possible may be advantageous in slowing this process (Canada, 2006) (Brown et al., 2006).

Further means to ensure containment will inevitably be put in place, notably a means to monitor the spread and any breach of containment, Nano-observation satellite swarms providing constant high resolution coverage of the lunar surface looking for signature biomarkers of the bacteria or their by-products could trigger countermeasures as a response. These countermeasures may take many forms, but such countermeasures may result in hazardous consequences for the lunar inhabitant crew should more localized mitigation of 'loose' bacteria prove unsuccessful. The suggestion of incendiary or vaporization munitions could be considered as a last resort. The specific utilization of fuel to air (modified for oxygen on board the weapon) or oxygen carrying daisy-cutter or nuclear warheads are not recommended but could be considered as a last resort. More localized mitigation may be the use of bi-liquid flame production or spraying of free radical rich compounds, high intensity UV lamps or laser ablation/heating or redirection of solar flux for solar thermal heating past bacteria coagulation temperatures.

### **3.3 Health**

Clearly human health is a critical element of any successful space mission. The challenging and creative work that must be accomplished in space can only be successfully carried out if individuals remain physically and mentally sound. A closed loop Moon habitat can be defined as a complex sociotechnical system<sup>1</sup> due to its nature of humans working in a complex technical system (Vicente, 1999). In order to work effectively, this system requires that health, safety and productivity are core considerations. The productivity aspects of a closed loop Moon habitat

---

<sup>1</sup> The interrelated characteristics of a complex sociotechnical system are the following: large problem spaces; dynamic, potentially high hazards; many coupled subsystems; automated, uncertain data; mediated interaction via computers; social, heterogeneous perspectives distributed, and disturbance management

have been discussed in varied sections of the report. Health and safety considerations related to environmental hazards are addressed here.

### **3.3.1 Physical Well-Being of the Residents**

Astronauts exposed to extended periods in microgravity suffer from accelerated bone demineralization, disuse muscle atrophy, and a deconditioned cardiovascular system. While countermeasures have been developed to mitigate these issues, their effectiveness is still far from perfect. If a lunar crew is to remain safe, healthy and functional during an 18 to 36 month shift at Luna Gaia, innovative countermeasures will need to be employed. Several countermeasures that are promising, but still under development, have been incorporated into the proposed health and exercise regime based on the assumption that they will be well tested and proven by the time Luna Gaia is in full operation.

When the force of gravity is reduced, as it is on the lunar surface, the level of downward force acting upon body fluids is decreased. In such an environment, fluids tend to redistribute towards the chest and upper body, leading to increased urine output as a consequence of the perceived 'excess' fluid in the thoracic cavity. The heart becomes smaller and the body learns to function with less fluid (Mukai, 2006). In microgravity the musculoskeletal system experiences a decreased load leading to both skeletal muscle atrophy and bone demineralization. In fact, considerable muscular atrophy is present in humans in as little as 5 days of space flight, and up to 1-3% of bone mass per month is lost in microgravity (Jones, 2006b). However, it is important to recognize that these rates only correspond to the level of microgravity in low Earth orbit. Medical scientists have not yet had the opportunity to study the rate of bone and muscle loss during long duration exposure to lunar gravity, which is 1/6th of Earth's.

For the purposes of this paper, the authors are working under the assumption that as the level of gravity increases, the rate of muscle and bone loss decreases. Furthermore, we are assuming that the lunar habitants will be engaged in more extra vehicular activities (EVAs) and thus more physically demanding (i.e. muscle and bone loading) work than crews presently working on the ISS. In view of these assumptions, it is likely that the overall time per day dedicated to scheduled exercise will be less at Luna Gaia than for crews working on the ISS.

The health and exercise regime designed for Luna Gaia includes a combination of exercise, non-exercise, and pharmacological countermeasures. The approach taken was to build upon the devices and protocols developed for the ISS with innovative or 'up-and-coming' technologies and techniques.

### **3.3.2 Physical Countermeasures**

#### *Conventional Countermeasures*

The specific ISS exercise hardware that will be incorporated into Luna Gaia's health facility includes:

- Treadmill (aerobic exercise, pelvic and femur bone loading)
- Cycle Ergometer (aerobic exercise with heart rate monitor)
- Resistive Exercise Device (exercises at near maximum strength for the major weight bearing muscles – hips, lower back, legs)
- Blood Pressure and ECG Monitor
- Medical computer
- Metabolic gas monitor
- Body mass measurement device

The ISS non-exercise hardware that will be incorporated includes:

- Lower body negative pressure (simulates gravitational force on legs and lower back)
- Loading ‘Penguin’ Suit (applies constant loading force of up to 70% of body mass to decrease bone and muscle loss)
- Pharmacologic treatment (medications, herbal, homeopathic, nutritional supplements)

### *Innovative Countermeasures*

Centrifuge-induced artificial gravity, while still in the development and testing stages, holds great potential for mitigating the negative effects of microgravity for long-duration space travel and habitation. A significant amount of research and resources are being invested into the development of this technology, and several comprehensive research programs are underway, and/or are being planned. A study conducted by Iwase (Iwase, 2005) at the Aichi Medical University in Japan, for example, found that centrifuge-induced artificial gravity with ergonomic exercise after extended bed rest could:

- suppress plasma volume loss,
- prevent fluid volume shift by the countermeasure load,
- counteract elevated heart rate and muscle sympathetic nerve activity after bed rest, and
- suppress exaggerated response to head-up tilt.

The International Multidisciplinary Artificial Gravity (IMAG) Project, a ground-based effort designed to assess the value of rotationally-generated artificial gravity as an effective multi-system countermeasure for long-duration space travelers, is also being planned (McPhee, 2004). The authors maintain that continuing research efforts in this area will enable the technology to mature and be incorporated as an integral element of Luna Gaia’s health and exercise facility. Another innovative countermeasure designed specifically for Luna Gaia is the Hydro Therapy and Storage Tank (HTST). Designed to be multi-functional, the HTST will play an important role in the habitat’s overall water storage system, will provide Lunar inhabitants with the physiological benefits of an omni-directional pressure environment in which to perform resistive exercises, as well as provide lunar inhabitants with the psychological benefits of a radiation and vibration protected ‘sanctuary’ in which relaxation and privacy may occur.

### **3.3.3 Personal and Social Well-Being of the Residents**

Research has shown that psychological factors such as stress, personality variables, intergroup relations, and sociocultural differences impact human behavior and performance. This is no different from missions performed in extreme environments (Dudley-Rowley et al., 2002). Most psychological studies conducted during space missions or in analog environments have provided evidence that interpersonal and cultural issues can disrupt group cohesion and interfere with the performance of mission tasks (Bishop, 2002). Therefore, the success of a complex mission, such as a closed loop lunar habitat, depends not only on individual, but also on lunar inhabitant ability to perform complex tasks cooperatively in a group structure. However, the study of psychological influences in a closed loop lunar habitat is complicated by the unique behavior shaping constraints of the lunar environment.



### **3.3.4 Behavior-Shaping Constraints on the Closed Loop Habitat and Lunar Environment**

Many studies have argued that humans' behavior and performance are shaped not only by psychological and psychosocial parameters, but also by situational parameters. Vicente refers to Herbert Simon's simple hypothetical example of an ant on a beach to further explain this concept. The ant's trail appears to be a complex, irregular path that is difficult to describe. However, in reality there is a complexity on the surface of the beach. According to Vicente, the ant's trajectory is shaped not only by the constraints of the ant's psychology, but also by the constraints that are imposed by the beach. This simple concept can apply to humans thus the identification of environmental constraints in the lunar habitat will be crucial to understanding human behavior in the lunar environment (Vicente, 1999).

The following are examples of behavior-shaping constraints on the closed loop habitat and lunar environment that will likely impact human behavior and performance. They may cause stress, anxiety, depression or conflicts among lunar inhabitants if proper countermeasures are not planned.

- High potential hazards in the environment: radiation, etc.
- Isolation - Residents will be isolated from friends and relatives and the distance between the Earth and the Moon poses communication delays and limitations.
- Artificial environment for working and living - Although lunar inhabitants will be acquainted with the habitat environment in simulations on Earth, simulations cannot provide 100% fidelity making the closed loop habitat on the Moon a novel environment.
- Potential for unanticipated events - The closed loop lunar habitat will be an artificial structure that will be tested as a whole system in the space environment for the first time during the mission. There is a high possibility for the occurrence of unanticipated events.
- Unfamiliarity, uncertainty and fear of unknown - The lunar environment is filled with potential hazards and is unfamiliar to the residents (e.g. – microgravity on the Moon, different visual cues, etc.). In addition to this, the working and living environment will be artificial and novel, with most outside information entering through a machine interface, typically a computer or TV projection. The likely effects of these artificial settings will be feelings of uncertainty and insecurity in relation to the lunar surroundings, especially when compared to living settings on the Earth.
- High adaptation to the environment is required - Residents must adapt to artificial environments in the habitat, lunar environment, etc.
- Less privacy than Earth - Most aspects of residents' lives on the closed loop habitat will be controlled for safety and research purposes compromising privacy of the lunar inhabitants.
- Less freedom and autonomy - On an environment such as Luna Gaia, human life is totally dependent on the systems, particularly the closed loop life support systems. As a consequence, the human inhabitants will have limited freedom to choose where to go and what to do.

Human cognitive competencies, along with personality variables and sociocultural differences in the context of environmental constraints on the Moon, pose different challenges to human performance and group functioning. These are increased by the duration and distance of a lunar mission. Failures in human performance have been linked to four major risks related to behavioral health and performance during long space missions (Exploration, 2005 ):

- poor psychosocial adaptation
- neurobehavioral problems
- mismatch between workers cognitive capabilities and task demands
- sleep loss and circadian rhythm problems.

### 3.3.5 Psychological Countermeasures and Mitigations

Occurrence of the above risks could jeopardize the health and safety of lunar inhabitants and mission objectives. As such, it is crucial to define the problems and to develop and evaluate countermeasures (Exploration, 2005 ). Current psychological countermeasures are based on preventative measures such as selection, training and monitoring. In addition, human cognitive capabilities and limitations are considered in the design of human-machine interfaces and tools. However, because of the unique characteristics of a lunar mission, new countermeasures and mitigation techniques are required.

#### *Crew selection*

Crew selection should be based on both individual criteria and group functionality criteria. Current selection criteria are mostly based on “select out” criteria which disqualifies people with clinical disorders such as schizophrenia, major depression and/or cognitive dysfunction. However, for long duration missions, such as a lunar mission, select in criteria becomes crucial. “Select in” criteria identify suitable personality characteristics for the mission. Psychological traits such as group identity, group commitment, motivation, sensitivity to self and others, emotional stability, maturity, etc. will be crucial for such missions. Researchers integrated data from ten missions<sup>2</sup> - three space missions and seven expeditions - and revealed that in general, larger crew size are more functional than smaller groups (Dudley-Rowley et al., 2002). The crews that functioned better and had fewer conflicts were crews of approximately nine persons. This study also showed that heterogeneity (e.g. - different genders, ages, and nationalities) and homogeneity of crews cause two different patterns of group functioning during mission intervals (Dudley-Rowley et al., 2002). Some levels of deviance and conflict among heterogeneous crews occurred at the beginning of the mission. However, heterogeneity in the group was beneficial later in the mission as crews were more likely to achieve innovative solutions. On the contrary, people in homogenous groups functioned well together at the beginning of a mission because they possessed similar training and background. However, similarities became tiresome, in some cases making it difficult to “think outside of the box”. In the case of Luna Gaia, a heterogeneous crew is recommended since the mission is relatively long (18-36 months), and the benefits associated with group diversity. This investigation also demonstrated that longer missions had fewer group conflicts because people had more time to get to know each other and socialize. It will be beneficial to select a physician or a professionally trained health officer for the Luna Gaia mission. Medical support from the Earth will be limited due to the distance and communications challenges.

---

Three space missions: Apollo 11, Apollo 13, and Salyut 7.

Four Antarctic expeditions: the western party field trip of the Terra Nova Expedition, an International Geophysical Year (IGY) traverse, the Frozen Sea and the International Trans-Antarctica expeditions.

Three Arctic expeditions: the Lady Franklin Bay, Wrangel Island, and Dominion Explorers' expeditions.

### *Training*

Training is another countermeasure to mitigate human behavioral and performance dysfunction during space missions. Pre-flight training includes a diverse range of cultural and language training to complement cross-trained professional skills. While in short-term space missions, task-based training is more crucial, skill-based training is more beneficial for long-term missions. Skills such as situational awareness, team decision making, and group cognitive management are also worth considering. Although the bulk of training will be during the pre-flight phase, ongoing training and re-training will continue during different phases of the lunar mission. Research has shown that the frequency of error occurrence increases as time passes from skill training (Gary T. Moore, 1992). Since a lunar mission is projected for 18 to 36 months, training and retraining during the mission should be planned. The on-going Crew Training and Support Systems Program at NASA-Ames may prove a very beneficial framework on which to base the Luna Gaia training program (Ames, March 23, 2006). In addition, since the closed loop habitat is heavily based on biological processes, we recommend some degree of training and understanding of horticulture, biotechnology and microbiology for the crew members.

### *Psychological Supports and Monitoring*

Psychological support includes monitoring of individual cognitive assessments, adaptations, and group functioning. Self-report monitoring and private conferences with a psychological professional throughout the phases of the mission are useful tools (Exploration, 2005). In addition, psychological support should be expanded to include the family members of the lunar inhabitants. Regular communication with family members will help the lunar inhabitants cope with the psychological stresses of isolation and mission challenges, and help their family cope with separation anxiety.

### *Interface design*

Interface design must provide adequate information to enable informed decision making. Further to this, there must be adequate communication between lunar inhabitants and Earth as well as within the lunar inhabitant group itself. The design should support the actions and planning of lunar inhabitants during regular performance as well as crisis scenarios. Interface designs must support all three levels of cognitive control: skill-based behavior, rule-based behavior and knowledge-based behavior. Skill-based behavior demands a lower level of cognitive control, rule-based behavior demands more cognitive control, while knowledge-based behavior demands the highest cognitive resource like problem solving tasks (Vicente, 1999). Different kinds of expertise are associated with different levels of cognitive control. The goal of interface design is to provide sufficient information for all three levels of cognitive control without forcing the user to use higher levels of cognitive control when it is not necessary. Proper interfaces design reduces crew cognitive workload and fatigue and consequently decreases human errors.

### *Workload Assessment and Function Allocation*

Excessive workload causes anxiety and stress (Vicente, 1999), thus there must be a realistic workload assessment. The workload assigned to the lunar inhabitants must be compatible with human physical and cognitive capabilities and limitations. As such, function allocation between humans and machines (e.g. degree of automation) and task allocation among lunar inhabitants must be planned carefully, logically and precisely.

### *Reducing Uncertainty and Fear of Unknown*

A closed loop lunar habitat is a novel artificial environment that poses uncertainty and insecurity. Therefore safety measures and redundancy in the system design are fundamentally crucial. In order to generate an atmosphere of security among the crew, lunar inhabitants need to be informed about all safety and redundancy precaution measures in the system. Useful tools for pre-mission mitigation could involve high fidelity simulations based on real lunar images and environmental parameters to familiarize the crew members with the lunar habitat environment. A tool such as this would enable the lunar inhabitants to practice different scenarios, solve problems and make decisions individually or as a team in a virtual closed loop lunar habitat prior to mission departure.

### *Increasing the Familiarity in the Living and Working Environment*

Previous investigations regarding human requirements in a lunar habitat have suggested adding features similar to the terrestrial working environment to the lunar base (Moore, 1992). Places such as a small library, study room, and recreation area are mentioned in conjunction with implementing familiar visual cues, color, light, etc. (Kubicek and Woolford, 1995). A newer idea is to add a sanctuary to the habitat for activities such as relaxation, yoga or spiritual experience.

### **3.3.6 Tests and Evaluations**

It is important to keep in mind that countermeasures must be tested in controlled environments such as laboratories and simulations and stringently evaluated. If a given countermeasure is efficient in the controlled environment, then field validation will be required. Only following successful completion of field validation and thorough testing and evaluation procedures, can a countermeasure be considered for space missions (Exploration, 2005).

## **3.4 Radiation**

### **3.4.1 Radiation Sources**

In the absence of the Earth's protective magnetic field, radiation exposure becomes of increasing concern. There are four sources of radiation lunar settlers can be exposed to. The two main sources of concern are galactic cosmic rays (GCR) and solar particle events (SPEs). Other sources for consideration include the Van Allen Belts, and artificial sources, such as radiation emitted from nuclear fission power generators (Tribble, 1995).

In the absence of the Earth's protective magnetic field, radiation exposure becomes an increasing concern. There are four sources of radiation to which lunar settlers can be exposed. The two main sources of concern are galactic cosmic rays (GCR) and solar particle events (SPEs). Other sources for consideration include the Van Allen Belts, and artificial sources, such as radiation emitted from nuclear fission power generators (Tribble, 1995).

**Galactic Cosmic Rays (GCR)** originate outside the solar system, for the most part within our Milky Way galaxy. GCR and high energy electrons are produced by supernova remnants, accelerated to nearly the speed of light with energies up to TeV (Harding, 1989). They diffuse throughout space and the solar system, delivering a constant source of high energy, low dosage radiation. The gradual accumulation of GCR limits the amount of time humans can spend in space safely. GCR are composed of approximately 85% protons, 14% helium and a 1% fraction of high energy and high charge ionized cosmic ray nuclei (HZE particles)

(Harding, 1989). HZE particles ranging in size from hydrogen to uranium (Clement, 2003) are extremely penetrating because of their high energy properties (Harding, 1989) (Rapp, 2005). Shielding composed of low atomic number materials, such as hydrogen, is the most effective at protecting against the hazardous HZE particles (Rapp, 2005).

**Solar Particle Events (SPE)** are the release of solar protons and heavier ions from the sun. Events can be classified as impulsive or gradual. Impulsive events are the result of solar flares, with time durations of several hours, and are characterized as electron-rich (3 He/4He) and heavy ion-rich (Fe, Mg). Electron-rich events are associated with H-alpha and X-ray flares, and type III radio bursts. Conversely, gradual events are more intense, have time durations in the order of days, and are electron poor (Bothmer). They are also associated with gradual X-ray flares, coronal mass ejections, and type II and type IV radio emissions (Reames, 1996). Because the particle influence of SPE are orders of magnitude higher than the cosmic ray influences, it is crucial to assess the biological effects induced by single event SPE. Gradual SPE are of greatest concern as they pose the greatest danger to the lunar crew due to the high long-lasting particle fluxes (O'Bryan).

**Van Allen Belts:** The Van Allen Belts consist of protons and electrons trapped by the Earth's magnetic field. Humans traversing between the Earth and Moon pass through these belts and are exposed to high levels of radiation. As such, launch vehicles have protective measures built into them to reduce risk.

**Artificial Sources:** Shielding of the proposed nuclear power supply (Section 2.3, Power) is required to protect against the neutron and gamma radiation (high energy, high frequency electromagnetic radiation) associated with the fission process.

### 3.4.2 Human Consequences of Radiation Exposure

There are differing responses to chronic and acute radiation. Table 3.4-1 (Clement, 2003) lists the expected acute radiation responses for increasing radiation exposure values.

Cancer and cataract formation as well as sterility are the main consequences of long-term radiation exposure; however, extremely high doses will induce death in any exposed tissue. Tissues with fast cell turnover rates such as: lymphoid tissue, gastrointestinal epithelial cells, bone marrow, epidermis in the reproductive system, hepatic tissues, pulmonary alveoli and the epithelium in the kidneys are at increased risk for DNA alterations. DNA alterations may lead to altered cell growth following moderate levels of radiation exposure. Females typically have a decreased overall body size and organ size, thus they have a greater susceptibility to radiation when compared to men (Clement, 2003).

Long-term consequences of radiation exposure, particularly GCR exposure, are not well understood. This absence of knowledge is preventing acceptable radiation exposure levels from being defined for missions traveling beyond LEO. Until results are obtained from ongoing scientific studies investigating these issues, LEO radiation limits are being used as guidelines for lunar, Martian and other deep space missions (Rapp, 2005). The last formal recommendations update for radiation limits in LEO was done in 2001 by the National Council on Radiation Protection and Measurements (NCRP) in NCRP Report No.132 (2001) (National Council on Radiation Protection and Measurements, 2000). These recommended dose limits are outlined in Table 3.4-2 and 3.4-3. Mission exposure predictions are based on point estimates of radiation exposure. Since the release of these recommendations in 2001, concern has been raised that these

**Table 3.4-1 Expected Medical Effects Following Acute Radiation Exposure**

Dose (Sv)	Probable Medical Effects
0.1 – 0.5	No effects with the exception of minor blood changes
0.1 – 1	5-10% of subjects experience nausea or vomiting; fatigue lasts 1-2 days, small reduction in white blood cells
1 – 2	25-50% nausea and vomiting, 50% reduction in white blood cell counts
2 – 3.5	75-100% nausea, vomiting, fever, with anorexia, diarrhea and minor bleeding; 75% reduction in a blood elements, 5-50% mortality
3.5 – 5.5	100% nausea, vomiting, fever, bleeding diarrhea and emaciation. Death of 50-90% in 6 weeks, survivors require 6 months convalescence
5.5 – 7.5	100% nausea and vomiting in 4 hours; 80-100% mortality
7.5 – 10	Severe nausea and vomiting for 3 days, death within 2.5 weeks
10 – 20	Nausea and vomiting within 1 hour, 100% subjects will die within less than 2 weeks
45	Incapacitation within hours, 100% subjects will die within 1 week

**Table 3.4-2 Recommended Organ Dose Equivalent Limits for All Ages**

Exposure Interval	Blood-Forming Organs Dose Equivalent (cSv)	Ocular Lens Dose Equivalent(cSv)	Skin Dose Equivalent (cSv)
30-Day	25	100	150
Annual	50	200	300
Career	See Table 3.4-3	400	600

Source: NCRP-132 (2001)

**Table 3.4-3 LEO Career Whole Body Effective Dose Limits (Sv)**

Age	25	35	45	55
Male	0.7	1.0	1.5	2.9
Female	0.4	0.6	0.9	1.6

Source: NCRP-132 (2001)

values may not adequately reflect actual exposure levels (Rapp, 2005). If this is the case, protection standards based on point estimate prediction values are not sufficient, especially for long duration missions outside the protection of the Earth’s magnetosphere.

A recommendation has been recently proposed to define exposure limits that raise the risk of cancer death following maximal exposure by no more than 3% (within a 95% confidence interval) (Hada and Sutherland, 2006). Effectively, the proposed modification to exposure value calculations has lead to all predicted exposure values in the 2001 NCRP report being multiplied by a factor of 3.5. This results in extremely high exposure predictions, which if correct, require extensive radiation mitigation strategies as well as limited mission durations.

Radiation mitigation is crucial to the survival of humans on the Moon. However, until we are able to accurately predict our exposure levels, and understand what form of radiation we are being most impacted by, effective radiation mitigation will be difficult to achieve.

### 3.4.3 Approaches to Risk Mitigation

The thresholds for electronic technologies and materials are typically higher than the maximum radiation exposure levels admissible for humans (Tribble, 1995). The recommendation for a conservative value of 40 cSv as the radiation exposure limit for humans (Table 3.4-3) will drive the overall habitat design. It is worth noting that total dose safety margins recommended for electronic technologies are on the order of 5 times the recommended exposure radiation limit (Tribble, 1995). Parts with safety factors between 2 and 5 may require additional testing and/or piece part traceability and safety margins below 2 shall be avoided. Sufficient safety margins can be achieved using combinations of different shielding techniques. It should be noted that current models for total radiation spectrum are insufficient. A meeting should be convened between groups like NASA and NOAA, and some funding found to gather more and better data and to develop more useful, health-specific models of the radiation environment.

#### *Management Approach to Radiation Mitigation*

For the success of a lunar settlement, all possible steps need to be examined in order to mitigate radiation exposure within budgetary and resource limitations. Several different approaches have been taken to minimize radiation exposure. In this section we will discuss approaches, including management, shielding, biological countermeasures, and post-irradiation measures. We will also discuss ethical issues for consideration.

#### *Launch Window*

The timing of the mission will coincide with solar minimum. However, periods of solar activity will be anticipated leading up to and following solar minimum when magnetic field inversions are strongest.

#### *Personal Dosimeters*

To carefully monitor individual radiation exposure, each lunar inhabitant will be required to wear a personal dosimeter. Dosimeters will also be installed on the outside of the space station to provide real-time information and characterization of the radiation at the lunar surface. There are commercially available electronic dosimeters which allow continuous monitoring and early warning as exposure maximums are approached. Devices such as these will be an integral component of radiation sickness mitigation.

#### *Monitoring Space Weather*

The National Oceanic and Atmospheric Administration's (NOAA) Space Environment Center announces an SPE is in progress when the dose rate of particles with energies above 10 MeV (space-suit-penetrating) is greater than 10 particles  $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$  (directional flux) for more than 15 minutes ("Commission on Physical Sciences and Board", 2000).

Current providers of space weather data and information, such as the Solar and Heliospheric Observatory (SOHO), NOAA's Space Environment Center, and the International Living with a Star program, allow for monitoring of the space weather environment. Furthermore, new technologies can be incorporated to help form an advanced system of monitoring space weather for the lunar habitat. The Solar Terrestrial Relations Observatory (STeReO), for example, proposed for launch in 2007, will use stereoscopic (3D) vision to construct a global picture of the Sun and its influences (Kaiser, 2006). This mission will provide the first-ever stereoscopic measurements to study the Sun and the nature of its coronal mass

ejections (CMEs). The satellites will trace the flow of energy and matter from the Sun to Earth, providing alerts for Earth-directed solar ejections. The adaptation of this system and associated technologies to monitor space weather for the Luna Gaia settlement will greatly increase the security and safety of the inhabitants.

### Surface Missions

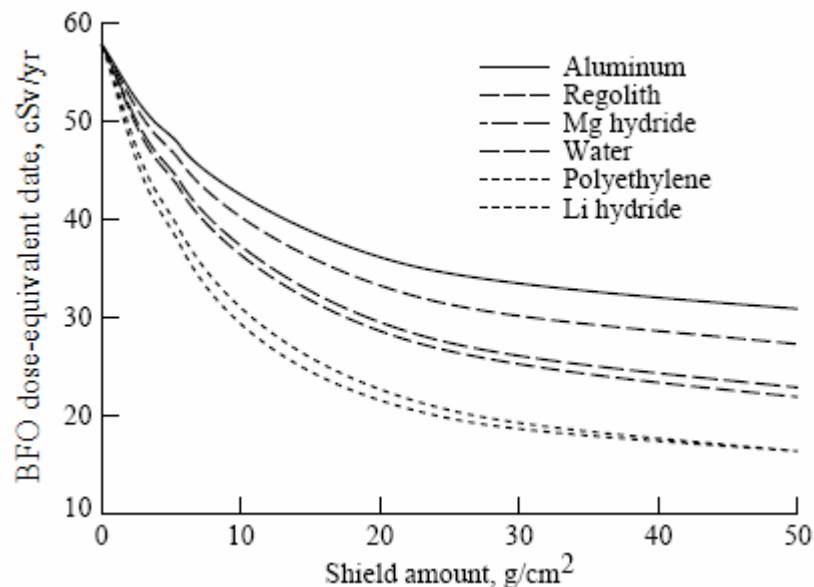
The unpredictability of solar flares allows a warning period of SPE of only a few minutes to hours. Distances of surface expeditions will be limited according to the phase of the solar cycle.

### Shielding Strategies for Radiation Mitigation

To provide maximum radiation protection at a minimal cost, several shielding methods are proposed.

### Passive Shielding

Figure 3.4-1 (Eckart, 1999) shows the protection effectiveness for some materials. Passive shielding stops charged particles through multiple collisions within the shield material. On the surface of the Moon it is possible to protect inhabitants from GCR with layers of regolith (Eckart, 1994). Lighter elements such as hydrogen, carbon, and oxygen, and their compounds such as water and plastic, are the most effective shields per unit mass (Eckart, 1994). Water and LiH are effective, but not as advantageous as liquid hydrogen and liquid methane. Liquid hydrogen and methane are potential fuels that could also contribute substantially to the overall protection if stored in large quantities. The most effective solid is polyethylene and composite materials (Stoker and Emmart, 1996). Composite materials have not been used as primary structures in the space environment, mainly due to their process-dependant properties and out-gassing. However, industry expertise is improving the potential for their future use.



**Figure 3.4-1 BFO Dose-Equivalent for GCR at Solar Minimum for Various Materials**

The following table takes into account the radiation exposure limit requirement of 40 cSv (Table 3.4-4) and data from *Strategies for Mars: a guide to human exploration* (Stoker and Emmart, 1996).



**Table 3.4-4 Shielding Requirements for 40 cSv**

Material	Density (g/cm <sup>3</sup> )	Required Shield Thickness (g/cm <sup>2</sup> )	Required Shield Thickness (cm)
Liquid Hydrogen	0.07	2.4	34.3
Liquid Methane	0.424	4.9	11.6
Polyethylene (composites)	1.0	5.5	5.5
Water	1.0	8.0	8.0
Aluminum	2.7	17.0	6.3
Regolith	1.5	30.0	20.0

### ***Passive Shielding - Fixed Facilities***

Locating the base in a crater at one of the Moon's poles provide shielding against the SPE radiation, protecting against approximately half of the isotropic flux (Eckart, 1999). Lunar regolith (or regolith concrete) will be used to provide overall base coverage, as it is more reliable over the lifetime of the base, and serves as a good micrometeoroid shield. Models indicate that a 20 cm thickness of regolith (30 g/cm<sup>2</sup> assuming a regolith density of 1.5 g/cm<sup>3</sup>) will reduce the blood-forming organs dose equivalent to approximately 30 cSv/yr for the GCR – Figure 3.4-1 (Eckart, 1999). Increasing the regolith thickness beyond 20 cm does not result in significant gains. Additional shielding is provided through materials utilized in the base structure (Table 3.4-4) and placement of the water tanks over laboratories and sleeping quarters.

### ***Passive shielding – Fission reactor***

Assuming 50mSv/yr (Table 3.4-3) is an acceptable amount of radiation exposure, placing the reactor in an excavated hole will provide acceptable radiation protection (WHO). Regolith moving equipment should be readily available from the ISRU mines (refer to Section 2.2.3, In Situ Resource Utilization for more details). Regolith could be used in combination with a reactor shield, or with a sufficient thickness (3.5m) to attenuate the radiation to acceptable levels.

### ***Other Considerations for Radiation Shielding***

#### ***Equipment***

Radiation affects equipment and materials in a variety of ways, including gas evolution, change in mechanical, electrical, and optical properties, and even complete mechanical breakdown (Eckart, 1994). Radiation effects should be mitigated through the base shielding and design of exposed equipment. Circuits under the base shield will be protected against less energetic particles. However, error correction and redundant circuit design should be used since the shielding will be less effective for more energetic particles. The exposure of solar panels to the entire radiation spectrum will induce rapid degradation in the lunar environment (maximum of 3 to 4 years, at 10% degradation per year, excluding effects of dust). If solar mirrors are the main power source for the lunar base, redundancy will have to be included in the solar panels in an accessible and replaceable manner to maintain the efficiency levels specified by the energy requirements.

#### ***Transportation***

For transportation between the Earth and Moon, the proper selection of materials and proper design of bulk shielding configuration will allow radiation shielding requirements to be met with passive shielding (Eckart, 1994). A similar approach

will be used for lunar surface vehicles. For a broader discussion of transportation and shielding, see Section 2.4 Transportation.

An innovative concept based on inflatable plastic materials technologies should be explored for the development of an Emergency Inflatable Radiation Shelter (EIRS) for lunar EVA missions. The EIRS would be designed to collapse into a compact package that could be carried on the EVA vehicle. While incapable of protecting the lunar inhabitants from all forms of radiation, inflatable shelters would help minimize radiation exposure should an unexpected SPE occur during a lunar EVA mission.

#### ***Shield Chambers/Safe Haven***

Early warning systems and the provision of dedicated shielded chambers will protect against temporal and extremely high radiation levels experienced during SPEs. Chambers will have a minimum shielding equivalent of 15 g/cm<sup>2</sup> of water (Eckart, 1999), providing personal protection against high energy particles arriving from all directions. An innovative proposal for multi-purpose annular tubes to which lunar inhabitants can retreat during SPEs is in consideration. Hollow tubes surrounded by an outer shell of water would provide lunar inhabitants with personal protection, as well as an optional sleeping area and/or quiet retreat.

#### ***Biological Countermeasures to Radiation Mitigation***

A secondary method to minimize the effects of radiation on the body is through the use of pharmaceutical radioprotectants. These compounds work to prevent cellular damage from occurring or aiding in the repair process following damage (Stanford and Jones, 1999). The field of radioprotectants is expanding, aided by continuing research within the field. There is some concern over the efficacy and toxicity of these compounds, and thus cocktails of several low dose radioprotectants have been proposed for long-term pharmaceutical protection from radiation (Stanford and Jones, 1999). During short duration radiation exposure, high doses of the more toxic radioprotectants can be used to mitigate short term, high risk periods (such as lunar sorties).

#### ***Post Exposure Response***

In the event a lunar inhabitant is acutely exposed to high levels of radiation, several countermeasures can be taken to minimize the risk of infection and hemorrhage resulting from bone marrow destruction (Herodin and Drouet, 2005). The first is the administration of compounds that slow apoptosis rates, particularly interleukin-3, stem cell factor, Flt-3 ligand, and thrombopoietin. Furthermore, compounds that help tissue repair and recovery such as tissue specific growth cytokines may be of considerable benefit in mitigating these effects. Finally larger doses of antioxidants can be given to help mitigate damage that is occurring. The key to the delivery of all these agents is time; the faster the response time following radiation exposure, the more effective these agents are at minimizing the health effects induced by radiation exposure.

#### ***Ethical issues***

The field of cancer biology is expanding daily and by the time crew selection for Luna Gaia begins, there will be exponentially more information regarding cancer-risk genes. Genetic screening could be implemented to select for lunar inhabitants without identifiable predispositions to cancer. There are many statements in favor and against the use of genetic screening, making it an area of ethical contention. This area will need to be debated and resolved prior to the commencement of lunar inhabitant selection.

The recommendation to define exposure limits that raise the risk of death from cancer following maximal exposure by no more than 3% (within a 95% confidence interval) (Hada and Sutherland, 2006) is still below the risk taken in some Earthbound occupations such as agriculture and constructions. Meeting this recommendation will require extensive radiation mitigation strategies (and expenses) as well as limited mission durations. Some interesting points to consider here include:

- Most of the projections and calculations of radiation risk in space are best guesses and theoretical models.
- It is unclear how much worse the lunar environment will be.
- Very little is actually known about the biological effects of low-level radiation exposure in space.
- The number of astronauts past and present is still too small to provide a useful statistical sample to compare with cancer rates in the normal population.

The human exploration of space consists of a specialized population exposed to specialized risks. Discussions around what is an acceptable level of risk, with consideration of other associated risks of space exploration (psychological, physiological, and launch), and previous eras of exploration, might result in new approaches towards setting acceptable risk levels.

## **3.5 Safety**

### **3.5.1 Lunar Dust**

Lunar Dust has the potential to prevent humans from settling on the Moon. It may be one of the greatest engineering, health, safety and sustainability challenges humans will face in the lunar environment.

In terms of health impact, in the terrestrial environment, extensive evidence confirms considerable pulmonary and cardiovascular effects of both acute and chronic exposure to particulate matter air pollution smaller than 10  $\mu\text{m}$ . Furthermore, chronic occupational exposure to dust, including asbestos and silica, is associated with the progressive worsening of non-malignant lung diseases. There is considerable concern that lunar dust may have similar or worse effects than terrestrial dust due in part to its sharp-jagged surface and charge carrying properties (Taylor et al.).

Apollo astronauts who performed extravehicular activities on the Moon reported acute exposure to lunar dust during removal of their extravehicular mobility suit and during return of the lunar module to the microgravity environment (Horanyi et al., 1998). No long term physiological effects of this acute exposure were noted, yet chronic exposure remains to be investigated. The human health risks associated with repeated low grade exposure to the hazardous lunar dust must be considerable over the duration of a Luna Gaia mission.

The lunar dust is electrically charged, which enhances its adhesive and abrasive properties (Stubbs et al., 2005), and mitigation countermeasures will be needed. Airlocks can serve as dust-off areas to reduce dust contamination of the habitat interior. The clean functional areas, galleys, electronics, and most science, should be separated from the airlock area to minimize dust contamination. Example methods and types of systems for dust control and collection are (Eckart, 1999; Junta, 2006):

- Wet wipes,
- Vacuum cleaners,
- Electrostatic precipitators,
- Docking of space suits in a fashion that keeps the space suit outside the habitat,
- Mechanical filtering systems, and
- Regolith sintering to construct a thin in situ pavement in the contiguous area where large-scale observatories are maintained (Wilson and Wilson, 2005).

In order to effectively mitigate the effects of lunar dust, future research is needed to understand the behavior of the Moon dust (Stubbs et al., 2005). Several key areas requiring research are:

- The size and concentration of dust in the lunar exosphere. This will show exactly how much dust gets ejected from the surface.
- The human physiological effects of chronic dust exposure.
- Discovering the surface electric field height profile, which will reveal both surface potential and the shielding scale length.
- How the composition of the lunar dust varies across the surface of the Moon and the consequences this may or may not have.
- Direct detection of the mass, velocity and charge of the dust grains above the surface.

Lunar dust has the potential to lead to mission failure. The more that can be learned about the composition, texture, structure and exposure consequences, the better our mitigation strategies will become.

### 3.5.2 Fire

Experiments have shown that partial gravity may be an environment which is quite conducive to fire propagation and combustion events. The rate of flame spread increases slightly as the gravitational level decreases to lunar levels. What is known from experiments is that flammability, fire spread, and combustion processes are very dependent on the gravitational setting (Eckart, 1999).

#### *Recommendations:*

- Atmospheric composition should be similar to the Earth's atmosphere ( $O_2$  concentration  $> 30\%$  is considered hazardous).
- Base construction with materials having high ignition temperatures, slow combustion rates and low explosion potentials.
- Reliable, automatic detection methods, avoiding spurious alarms (ionization detectors, and photoelectric flame detectors).
- Suppression with  $CO_2$  or  $N_2$  (water is not recommended since the most of the fires have an electric origin).
- Oxygen masks easily accessible.
- Atmospheric ventilation switched off when a fire is started.
- Cleaning (severe fire) by depressurizing the affected modules, and venting the contaminating atmosphere to space.
- Cleaning (small fires) with portable contamination control device. (Kubicek and Woolford, 1995).

### 3.5.3 Temperature Extremes

In the dark environment of the crater, surface temperatures approaching 40 K, temperature regulation needs to be considered both inside and outside the habitat to ensure lunar inhabitant health and safety. With this in mind, temperature regulation systems have been incorporated into the Luna Gaia habitat and space suit designs.

### 3.5.4 Contamination

Contamination of an environment is the uncontrolled or un-cataloged transfer of biological material, potential life forms, or other potentially hazardous substances (Darling). We will outline and define contamination issues, with recommendations for protocols, technological procedures and standards. Recommendations related to legal frameworks, policies, and ethical considerations for planetary protection will be considered in Chapters 4 to 6

#### *Biological Material and Potential Life Forms*

The Moon is considered a “dead” celestial body – there is no evidence that indigenous life exists there now, or ever has existed there. However, there are other locations in the solar system where life potentially exists. The possible threat of introducing a replicating biological entity of non-terrestrial origin into Luna Gaia and/or the Earth’s biosphere is of significant concern (Council, 1992). The Moon’s inhospitably to life and close proximity to Earth makes it an ideal location for the remote study of specimens from extraterrestrial bodies.

For celestial bodies, contamination issues typically include both forward and backward contamination. **Forward contamination** is defined as the accidental contamination of other worlds with microbes, such as viruses or bacteria, brought from Earth (Council, 1992). Considerations for forward contamination include controlling contamination levels on the Moon, contamination of Mars on sample return missions, and contamination of Martian samples. **Backward contamination** is defined as the accidental delivery of microscopic biological contaminants from extraterrestrial worlds to Earth. However, this definition will be expanded to include accidental delivery of microscopic biological contaminants to the lunar base. Backward contamination would most likely occur as a consequence of returning sample-return probes or crewed missions to celestial objects with potential for life.

#### *Forward Contamination and Prevention: Moon*

Though terrestrial organisms have virtually no chance of survival on the surface of the Moon or Mars (Klien, 1991), measures should be in place to monitor and control excess forward contamination and microbe mutations at the lunar base. Modern molecular methods, such as DNA amplification and identification using polymerase chain reaction (PCR) and gene chip arrays, may prove effective at detecting and identifying biological contamination (Council, 2002). Automatic monitoring systems should also be developed and implemented.

#### *Forward Contamination and Prevention: Mars*

On sample return missions, the threat of contamination of Mars is of great scientific concern (Darling). For this reason, microbial cleanliness of spacecraft on sample return missions is important. Sterilization standards should be implemented during the design and manufacturing of spacecraft components, with cleaning standards at least equal to, if not superior to, Viking levels (Task Group on the Forward Contamination of Europa Space Studies Board Commission on Physical Sciences, 2000).

### ***Backward Contamination and Prevention:***

#### *Mars Samples*

While the risk of large-scale effects of contamination at the lunar base by Martian microorganisms is low, the consequences are potentially serious. The National Research Council's (NRC) report, Mars Sample Return (Council, 1992), issued the following recommendations:

- Planetary protection measures should be integrated into the engineering and design of a sample return mission as early as possible in the planning phases.
- Martian samples should be contained and treated as though potentially hazardous until proven otherwise. Integrity of containment should be maintained through reentry of the spacecraft and transfer to the appropriate receiving facility.
- Robotic missions rather than crewed will obviate the need to place astronauts in quarantine.

#### *Facilities to Accept Mars Sample*

A panel of scientist will be created to establish a consensus on the goals and approaches prior to the receipt of the material, and to create a multi-disciplinary protocol for the initial evaluation of samples returned from Mars. A stringent biological containment facility (minimum of BSL-4 lab (Committee on Planetary and Lunar Exploration, 2002)) will be fully functional at least two years in advance of the sample return. It will include technologies for the detection of life, including optical and scanning electron microscopy to search for possible microbial structures, equipment for chemical analysis of biogenic compounds (including staining techniques), and facilities for the sterilization of equipment and samples potentially containing biological contaminants.

#### ***Sterilization Technologies***

Sterilization technologies include the use of heat, radiation, or chemical treatment. NRC recommendations for Mars sample return procedures (Council, 1992) include:

- If sample containment cannot be verified en route to the lunar base, the sample, and any spacecraft components that may have been exposed to the sample, should either be sterilized in space or not returned to the base.
- Controlled distribution of un-sterilized materials returned from Mars should occur only if rigorous analyses determine that the materials do not contain biological hazard. If any portion of the sample is removed from containment prior to completion of these analyses, it should first be sterilized.

#### *Technological Development and Earth Applications*

Research and development of new and improved technologies will reduce contamination risks, while presenting opportunities for Earth applications. Recommended areas for R&D include:

- Sample containment

- Sterilization techniques for suits, laboratory cabinets, tools, and containers, as well as measures to destroy more resistant microbes than those commonly studied in BSL-4 labs
- Sample cleaning, cleaning validation, maintenance of biologically clean work areas, encapsulation and containerization

#### ***Quarantine and Certification of Martian Sample***

A protocol will be developed for the detection of life and biohazards, and the quarantine and distribution of samples. It will be drawn from existing protocols (i.e. COSPAR guidelines, *The Quarantine and Certification of Martian Samples* (Kaiser, 2006)), and standards adopted by the International Council for Scientific Unions (ICSU).

#### ***Hazardous Materials off-gassing***

Material off-gassing can be of concern for overall health, particularly the production of polyaromatic hydrocarbons. The potential toxicity of off gassing needs to be considered in the selection of materials for the lunar habitat, as well as appropriate systems for monitoring toxicity levels. Technologies and standards will be developed, with consideration of applications from the Mir, ISS and shuttle missions (Office, 2006).





---

# Philosophical and Societal Issues

In early 2006, NASA Ames Research Center Director provoked us by asking “How do we sustain the vision for space exploration to lead to settlement? How do we afford it? How do we nurture it?” (Worden, 2006) These provocations leave no time for analysis, forecasting, or prevention. They are an immediate and stimulating reflex on a quest for long-term solutions. They seek to realize a vision already established in the psyche of our people, governors and indeed, this project. Luna Gaia is a working document towards a responsible and ethical framework of inquiry and recommendation in response to this challenge.

Following the UNESCO strategy for proposals for international action in the field of ethics of outer space (Pompidou, 2000) our enabling framework is divided as follows:

- International Implications: an international instrument on the ethics of outer space (normative actions)
- Ethics: overarching philosophical principals and draft decisions particular to Luna Gaia: (adopted action)
- Social Governance (precedence actions)
- Sustainable Management: propositions for international strategies to assist member states with the ethics of outer space (capacity building action)
- International Implications

Environmentalist David Suzuki argued that it would take decades to learn about the Earth’s eco-system after the Biosphere II project, let alone determine whether the principals would be self-sustaining or self-generating units for future use in outer spaces (Suzuki, 1993). Notwithstanding the risks and inherent challenges of this project, we seek to harness the know-how, to decide on know-who, to understand i.e. know-why, and to reconcile the know-when in our evolutionary development, as a species with advancing ambitions for outer space habitation. Furthermore, we ask: what exactly does this mean? The following paragraphs briefly introduce the scientific, economic and social rationales for the Luna Gaia vision and the knowledge of global effects and understandings that may follow.

## 4.1 Survival of the Earth’s Biosphere and the Human Species

It is well documented that space technologies and applications provide critical data to contribute to our understanding of the environment and our ability to manage our own natural resources. Space technologies and applications are able to provide data on ‘what we have’ and ‘what we have not’. For example, space-based Earth-monitoring systems increase our understanding of climatology and meteorology. Such information can be applied to agriculture, transportation and natural disaster early warning detection systems. Space communication and observation technologies also provide and determine data in support of precision finding and navigation techniques for land, sea and air securities, activities and conservation.

We can also deduce that the Earth's energy requirements will increase two or three times by 2050 according to the current rate (ESA, 2000). Despite strong concern from environmentalists, and the lack of proven capital and technological resource, the argument for harnessing off-Earth energy sources becomes very persuasive when supported by this data.

The Lunar Gaia model continues to develop technologies and application for the protection of the Earth's biosphere and the human species. In a doomsday light, Luna Gaia could be seen as a contingency against the extinction of humanity in the case of self destruction or natural disasters. The project continues the search for signs of life beyond our own, promising to bring back samples and developing vital survival skills and technologies. Should the survival of our species be threatened by an impact with a large asteroid or a nuclear war for example, Luna Gaia will be an alternative off-Earth settlement enabling the survival of human life. Furthermore, it actively advances knowledge for missions to other celestial bodies.

#### **4.1.1 Prosperity**

The immediate prospect of Luna Gaia provides many new areas of research, employment and Earth-based application. These in turn promise concepts, designs and operations that could improve standards of living, generate economic opportunity, access to new resources material or otherwise, and the prospect of rapid technological development and cross-fertilization of ideas, new visions and shared dreams. Earth-based space industries including the technological and intellectual property of the sector also contribute to the dissemination of scientific and technological culture internationally (Refer to Chapter 8 Earth Applications).

#### **4.1.2 Curiosity: The Quest for Knowledge**

Space exploration technologies have provided valuable data and insight into the formation of the universe, the planetary system, the sun and Earth. The quest to further human experience, garner new knowledge and stimulate (or sate) the imagination continues as a driving factor of the space exploration of today, and for tomorrow. For example, human understanding of the universe expended rapidly when the USSR first launched the Sputnik Satellite into space in 1957. Sputnik traveled at new angles of elevation and enabled scientists to collect new and precise information about the Earth from space. The observations and readings generated not only generated an unprecedented amount of measurement about the systems of the Earth, but it contributed to an historic shift in human perspective. We, humanity, thought of ourselves in the universe from a new point of view.

One of the advantages of sending humans into space to continue exploration is their ability to be able to synthesis the 'qualities' of the experience; to be able to extrapolate and respond to real-time encounters; to demonstrate courage, determination and make judgments and decisions based on analysis in complex situations; and to be able to 'report back' findings from the first person. The very idea of traveling into outer space is an abstract concept creatively explored in literature, art and the dreams of people throughout the ages. The intervention and support required to launch into, and then survive in outer space, is well-beyond the means of most of people. The continued pursuit of knowledge is driven by an overwhelming curiosity to understand the natural environment, the reasoning and origin of our existence and our desire for supremacy and evolutionary survival. Astronauts, Cosmonauts and Taikonauts are therefore our ambassadors *'feeling and sensing'* on behalf of all humankind.

### 4.1.3 Growth: New Habitats for Life and New Frontiers

Luna Gaia proposes to establish new habitats for life, new avenues for life science and research and more importantly the opportunity for exploration into new frontiers for humanity. In situ human presence is not ‘needed’ to continue interplanetary and wider space exploration related to physical and chemical experiments in space. Nevertheless, while the next generation of lunar settlers will participate in biological and medical studies in the absence of gravity, they will also act as envoys representing humanity in the search for life beyond that which we know. In the National Space Commission Report ‘Pioneering the Space Frontier,’ 1986, US President John Fitzgerald Kennedy states *“the pioneering spirit is part of the heritage of mankind...in recent decades, a new frontier has opened up to us, confronting humankind with its biggest and most promising challenge of all; the frontier of space.”* (Pompidou, 2000). These comments remind us that technological, economic and scientific needs aside; humanity is driven by the continual need for discovery and adventure to give the impression of power and positively reinforce our will to survive.

## 4.2 Ethics

*“Ethics is a specific discipline and ethical principals are not identical to legal, scientific or technical principals. However, it is clear that existing space law is based on some more or less explicit ethical principals. An international instrument should articulate ethical principals that are not conflictive with existing space law and that could be internationally proclaimed. Ethical principals should be considered as moral guidelines for activities undertaken in outer Space. Whether they should have binding power is not decided here. First of all they provide a framework for international action in various dimensions: educational, social and political”* (Pompidou, 2000).

The following paragraphs discuss the ethical significance of the dimensions of space: as a place, as a tool and as a perception; the ethical implications of space technology, and its impact on the ecology and biology of both terrestrial and celestial planets; the dual use of technology; the management, sovereignty and power in outer space and the notion of outer space settlement.

### 4.2.1 Philosophical Framework

Luna Gaia must consider the vision of returning people to the Moon as a significant opportunity to give renewed consideration for the development of more appropriate, advanced systems and infrastructures, technologies and philosophies. It is our responsibility to ensure that future generations are considered in our recommendations – not only the continuing generations on Earth who will have to make significant adjustment to the possibility of human interplanetary settlement – but the future generations of life which may vary in status, constitution and heritage well beyond our current imaginings.

The Gaia hypothesis, as developed by James Lovelock and Lynn Margulis looks at the whole biosphere as an interdependent living organism (Lovelock). The GAIA hypothesis, in many respects follows a more holistic perspective of ‘life’ as seen in some of Eastern cultures such as certain streams of Buddhism (Zurr, 2004). This is a fitting framework for the Luna Gaia project as is not the purpose of this document to derive singular ethical framework enablers for this vision, nor is it the intention to explore the nature of the sanctity of life axiom; rather we seek to question and discuss the principal assumptions defining what life is, and what it might come to be, through pluralistic authorship and mutual respect.

### 4.2.2 Human Rights

To paraphrase the National Space Society charter of 2006 (Society, 2006), we declare that Luna Gaia stands for the active pursuit and promotion of human settlement beyond the Earth, with scientific inquiry and exploration as important precursors. Luna Gaia advocates any and all methodologies that support achievement of our vision in an ethical manner consistent with the preservation of fundamental human rights.

In order to promote these principals, the Luna Gaia project proposal will be considered a working document, capable of taking the appropriate action to foster the progress of ethics and its application in technologies and methodologies, based on the respect for human dignity, respect of human rights and fundamental freedoms.

### 4.2.3 Gaia Ethics

It is imperative that ethical principals are incorporated into the decision-making process at every level. The moral decision making process should encourage public awareness of issues and motivations regardless of their foundation. Furthermore, these procedures should be transparent and fair. Access to data rights must balance the need to respect privacy, to protect data and to allow for an accessible and open public involvement and benefit. *“Ethical requirements apply even when legal requirements do not. They constitute moral – or ethical – obligations” (Pompidou, 2000).*

Gaia ethics should reflect a degree of respect for the terrestrial, circum-terrestrial and extraterrestrial environments. The Gaia hypothesis seeks to protect and preserve life and resources; to reflect the principa embedded in international law in relation to issues of contamination, genetic manipulation and the use and exploration of space with respect to the common heritage of humankind.

### 4.2.4 Sovereignty and Power

Space exploration has been historically perceived in geopolitical terms. Post cold war space-related activities were associated with political and economic posturing and human space-related activities were particularly aligned to state-driven efforts to garner national power and international sovereignty. Today, the perceived risks and social barriers are less state-focused.

State-led space related activities are in step with public private partnership activities and private operators. Commercial space-related research, development, exploration and marketing have inspired both strong competition for access to space resources and a shift in power. These drivers are putting pressure on policy and law framework enablers that reflect new relationships relating to trade, commercialization and commercial operation in space. For some commercial entities this means cooperation and for others it signifies considerable competition. Bilateral and multilateral agreements enable developing countries, small companies and individuals to build their capacity to participate in generating outer space-related opportunities in the ‘space market’. For others, common heritage principals, national space policy limitations, governmental obstacles to commercialization, and political/ economic issues continue to influence the sector. [See Chapter 5 Policy, Chapter 6 Law]

### 4.2.5 Risks

While every effort has been made to focus on the biological, psychological, social and environmental stressors that affect human performance function and behavior in an extreme environment – especially considered in the architectural design – we also acknowledge that there is a unique opportunity to redraw the ethical

boundaries of human experimentation and the expectations we hold for our settlers. Note the use of term: settler. We are no longer considering the risks of crews or short-term occupants and inhabitants of off-Earth spaces. The current recommendations and risk analysis processes related to human space flight are inadequate. The acceptable risk margins are no longer applicable when the parameters of consideration are compounded by the magnitude of the undertaking – particularly the long exposure rates and significant mission duration for the mission architecture as a whole. As national states change ruling parties, as technologies and protocols become engrained into the political fabric of the space industry, policy-makers need to be informed of the real risks to humans and to make informed decisions about how to minimize such risks about the immediate mission requirements and the long term future of space settlement.

A rigorous process of re-evaluation is recommended to consider the rationale and ethics particular to the current legal frameworks and how they may need to be adapted for the specific considerations of lunar settlement. (Refer to Chapter 4.4 Social Governance) For example, the notion of Genetic screening should be delineated from genetic testing (Ref. Ch 2. Health). Previous astronaut selection considered genetic testing as a critical tool for evaluating the suitability of undertaking a mission. Luna Gaia authors continue the tradition of this thinking with the knowledge that aspirations for a 'healthy crew or settler' can be ethically misguided and compromising. Genetic control of the human population, or any form of 'genome cleansing' could easily slide into eugenics. As such, we acknowledge that there needs to be a well scrutinized rationale for the use of this selection methodology. Similarly it is important to ask, is it still acceptable to use out dated risk-analysis tables which delineate acceptable levels of radiation shielding based on gender and age? (Refer to Section 3.5 Safety)

A complete re-examination of the policies relating to bioethics is recommended. Issues such as informed consent, right to privacy, freedom of access to information, pharmacological intervention, human enhancement technologies and human rights, contamination and a wider discussion of the risks and protocols of the eventual contact with new forms of life.

### **4.3 Social Governance**

The opportunity to develop social governance principles for Luna Gaia calls for a renewed questioning of the foundation of being and existence. This questioning requires organized, ethical consideration of our actions, our motivations and even broader reflection to identify what humanity has been and what humanity may become. Conscious construction of such a forum presupposes the need for cross-cultural, cross-disciplinary and international debate from the grass roots and elite thinkers of our time. Ideally, this process needs to be free from intimidation, corrupting persuasions and blinding bias, but sensitive enough to consider the exchange of ideas and experience that reflect the varied value systems of many peoples and national states. For example, it may be ill-advised in this instance to use present and historical frameworks that are derived from political, societal, economic and terrestrial points of reference. Furthermore, such a forum has a duty to strengthen the rights, freedoms and protection of all life. It must be founded on a moral solidarity that recognizes the constitutional differences and possesses the power to characterize the socio-cultural contexts of lunar-based life-forms and the margins of lateral control and heritage particular to this unique interplanetary perspective.

Very few individuals live in a state of exception. Even fewer live in an exceptional state. This will not be the case of future lunar inhabitants. Philosophically, the

human inhabitants of Luna Gaia would be outside existing Earth-based jurisdictions. Settlers would require a new charter to contribute to the maintenance of peace, security and fundamental identity differences between terrestrial and lunar constructs. The current complacency in the face of this challenge illuminates some difficulty in permanently adjusting to the advances of ‘another world’. Inevitably the issue must be addressed. The process of developing a preamble for interplanetary rights, liberties, justice, and respect – based on peace for all and without discriminatory charters of class - should commence immediately. A steering body should be established to coordinate a forum for moral questioning and reasoning in relation to the social governance of Lunar Life. Preliminary membership may include representatives from COMEST, UNESCO, United Nations, ISSC and the ICPHS. The first responsibility of the committee shall be to identify the freedom to space-related information and the dimensions of what constitutes ‘life’ i.e. humanoid, alien, lunatic, genetically modified organism, semi-living tissue, cyborg, nanobot, and so on. An analysis of communication instrumentation and the processes for long-term dialogue should follow, based on the assumption that lunar social governance frameworks will reflect the specific dimensions of life on Luna Gaia and eventually making them independent of Earth-based frameworks and jurisdictions.

## **4.4 Sustainable Management**

### **4.4.1 Access to Data**

Definition of a common standard of operation, data collection and information transfer system for all scientific activities to include activities conducted both in Lunar orbit and on the surface is preferable. Consideration of an international infrastructure for data relay, cross correlation and dissemination of such information should also be undertaken to include remote sensing observation missions, lunar exploration, lunar environment monitoring and preparations for human/robotic missions advancing the prospect of human settlement on the Moon.

We advocate the establishment of an international scientific working group to be responsible for recommending networked instrumentation and protocols. Its role would be to provide guidance to decision-makers - via interested agencies and organizations – on recommendations the geophysical/environmental status of the Moon, Moon/Earth-Moon observations, natural phenomena for the management of custodial transfer of information between states and a coordinated analysis of impact factors between states. Furthermore, an ethics of communication must be established in relation to media, education, and the circulation of materials. Freedom of expression should consider the impact of cultural identities and national policies on the option of non-disclosure for case-sensitive material for example.

### **4.4.2 Geophysical Network Instruments**

Geophysical Lunar exploration should continue at a range of specific target sites, most predominantly at the Polar and Equatorial regions. Definition of a common standard—somewhat akin to the seismic, magnetic and radiation monitoring networks on Earth- should be to ensure a coordinated analysis of the instrumentation, calibration and data relay at a reasonable rate with equitable access (Agency, 2006).

### **4.4.3 Communication and Information System**

An effective information and communications architecture should be developed at the initiation of the Moon settlement mission. It will be vital to ensure the standardization of communication and information architectures, establishing pathways to validate the data flows, processes to verify the retrieval processes and continual monitoring of the system access and efficiency of all systems management. A task force should be established to study the issues concerning priority routing, forwarding and storage configurations; congestion and flow control; fragmentation and assembly; security and the management and custodial transfer of data between states and partners to design, install and operate local and distant communications systems networks.

**Local (Moon- Moon) Communications:** Local intra-lunar communications systems will need to establish in the earlier phase missions for remote-sensing observations mission development. We recommend first phase mission and payload technology development towards a fully operational Global Lunar Navigation and Positioning Systems (Lunar GPS). This will also be paramount for subsequent deployment of robots and human and the continual monitoring, validation, calibration and analysis of knowledge of lunar-centered activities, human or otherwise.

**Distant (Earth – Moon) Communications:** Installation and operation of an InterPlaNetary (IPN) Internet network) would be effective. Current research into IPN delay-tolerant network architectures are focused on enhanced disruption and fault tolerance network architectures using bundle delivery protocols (K. Scott, 2006). Broad research and development incentives could enable a convergence of protocols and technologies. Advancing end-to-end communications may be dependent on public/private partnerships to consolidate existing technologies and properties related to installation nodes and endpoints, time stamping and time synchronization.

### **4.4.4 Mission Documentation**

It will be vital to ensure the standardization of communication and information architectures, establishing pathways to validate the data flows, processes to verify the retrieval processes and continual monitoring of the system access and efficiency of all systems management. In addition to retrievable digital data storage and back up systems, collection and proper archival of data such as drawings, analyses and test data is also very important.

### **4.4.5 Protection Taskforce**

An International Governmental Protections Taskforce (IGPT) should be established to monitor mission disclosure policies, coordinating with the international scientific taskforce and relevant regulatory authorities to register, monitor and analyze mission data in close-to real time. Lines of communication for disseminating environmental protection information and managing global and interplanetary emergencies and/or natural phenomena should be derived by policy-makers represented by the IGPT respecting the ethos of the Outer Space Treaty (1967).

### **4.4.6 Education, outreach, information and mediation pedagogy**

In order to promote the general principals outlined herewith, states should endeavor to promote the dissemination of information through education networks to foster the continued ethical consideration of space related activities

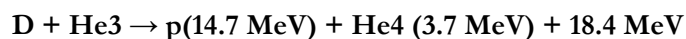
and exploration. Mediation pedagogy should be outlined in accordance with the guiding philosophical principals of the Luna Gaia project in addition to consideration of the mission statements of relevant supporting organizations. Appropriate, informative, insightful and engaging public outreach from a variety of media and sources, should also be encouraged to raise much needed awareness and public debate about the issues and challenges of outer space. Artists, educators, journalists, scientists and academics should be actively supported to action these principals in a highly visible and direct fashion. Endeavors should seek to encourage wider access to, and information transfer of, scientific and ethical knowledge and far reaching discussion and debate with participation at local, national and international levels.

## 4.5 Future in Space

Technology developed for a closed loop lunar habitat will pave the way for mankind's future in space. The techniques used in creating a closed loop habitat for example, can be used on other space missions in a phased progression that will continually decrease the reliance on re-supply from external sources. For instance, establishing long term settlements on Mars will likely be similar to that for the Moon but will need to utilize different in situ resources, as quick re-supply missions from Earth will not be possible. Furthermore, missions to Earth-Moon, Earth-Sun libration points or deep space travel will require the same technology but will need even more independence without in situ resources. A closed loop lunar settlement, expanding and building upon current research, will further enhance our future in space and enable mankind to journey from the cradle. It is therefore imperative that we establish a critical path towards future visions and understand the foundations that we lay for future applications and utilizations of lunar resources.

### 4.5.1 Lunar Helium-3 as an Energy Source

A very strong economic and resource-driven factor that drives the establishment of a permanent human settlement on the Moon is the mining of helium-3 as an energy source for use on Earth. The Apollo missions confirmed that solar winds have deposited large quantities of He3 on the lunar regolith over billions of years. It is not surprising that the identification of helium-3 as an efficient fuel source has led to increased commercial interest in lunar settlement inspiring research and development of transportation, mining and procurement techniques to support helium-3 reactors on the Moon (P.E., 2006). Helium-3 is present on the Earth but it is very limited, expensive and problematic. Helium-3 is a byproduct of thermonuclear weapons maintenance and a result of tritium decay. Unlike present Earth-based nuclear reactors however, helium-3 could be used in a neutronic fusion reaction with little waste. An example of this type of reaction occurs by mixing deuterium, (normal) helium, a proton and a light, non-radioactive isotope of helium called He3:



The single high-energy proton byproduct of the helium-3 reaction can be contained by electric or magnetic fields to generate electricity 'cleanly' and directly. The nuclear fusion reaction between 0.67kg deuterium and 1 kg helium3 produces 19 mega-electron volts and kilo-electron volts (megawatt-years) of energy for example (Schmitt, 2006).



*Second generation fusion reactors, using  $^3\text{He}$  and Deuterium, give rise to far fewer neutrons, at the source of radioactive waste and radiation damage. Third-generation fusion, in which Deuterium is replaced with a  $^3\text{He}$ - $^3\text{He}$  reaction produces no neutrons whatsoever (Schmitt, 2004).*

The by-products of the helium-3 reaction would also produce hydrogen, methane, water and nitrogen to be recycled into the life support systems. While this could in theory be a significant advantage for the Luna Gaia model, it should be noted that the extraction of this isotope from the Moon is not an easy task, nor does it serve to abolish Earth-based nuclear waste and/or safe handling issues. The risks to the lunar environment are high as the difficulty of extracting helium-3 from the lunar surface may be damaging as well as time consuming, with little return in useable fuel. The cost to establish and operate a nuclear ‘plant’ of this nature would also be significant.

In order to extract helium-3 from the Moon, the regolith must be mined and then heated to approx. 600°C. This would require a permanent ‘mining’ and operations base with processing and refining capabilities including a volatile extraction and agitation unit. These activities would require a significant infrastructure comprised of terrestrial-style mining technologies and a new, proven nuclear fusion reactor.

While it is not the intention of this project or report, Luna Gaia is the first step towards developing an economic geology that supports lunar-based mineral extraction techniques and the basic infrastructure for first generation helium-3 fusion energy production. Furthermore, future applications of helium-3 reactors could include their use in fusion propulsion devices for long-term interplanetary missions. It is important that we ask: Could the next generation of space craft use helium-3 for future missions? Will Luna Gaia exist not only as a lunar habitat but also as a re-fueling station for missions to other celestial bodies?

#### **4.5.2 Future Mission to Mars and Beyond**

*“As humans and robots work together exploring the Moon and Mars, NASA spacecraft will continue to send back scientific data from throughout the solar system, laying the groundwork for potential human journeys.”*

Luna Gaia concentrates on the idea of human habitability and the specificities of a bio-regenerative life support system. The model we propose considers the requirements of long duration habitat and maintenance. It considers a holistic framework enabling process by preempting new social governance attitudes while at the same time, attempting to close the loop with little dependency on re-supply and in-situ resource utilization. These considerations are fundamental to the context in which we have prepared this document as future missions to Mars and beyond are placed higher on the priority list for humanity.



---

# Policy Issues

## 5.1 Objectives of Sound Policy

The notion of a permanent settlement on the Moon will undoubtedly contribute to a myriad of debates spurred by the public and policy-makers alike. The success of Luna Gaia hinges upon developing a cohesive framework that considers crucial initiatives that must be resolved to enable mission success; to borrow from a systems design paradigm, these issues are the ones identified within the critical (policy) path.

A plethora of policy drivers will play an important role in determining the feasibility and success of developing an artificial environment at the local and international levels. The four main policy areas are: political, economic, scientific, and societal domains. Each of these core areas serves to influence the other, often with broader consequences for ethical, legal, domestic and international regimes. Through a careful assessment of these drivers, we are able to identify some critical policy issues that must be resolved for Luna Gaia to go forward.

### 5.1.1 Political

While freedom of access is guaranteed to all parties to the Outer Space Treaty of 1967, no stipulations exist for the development of an international governing body on the Moon. Political drivers will play a large role in delineating government ambitions, the need for international coalescence, and the terms dictating negotiations and conflict resolution between parties. Accordingly, selling the mission to the public and gathering grass roots support from various constituents will also be part of the political policy and public outreach. Thus the report will recommend the development of an international agency that manages these issues.

Although outside the scope of the report, military cooperation between nations via the lunar base will be briefly addressed. The Outer Space Treaty makes clear that military installation on celestial bodies is expressly prohibited. However, international agreements could be forged that call for the use of joint operations via the Moon to counter serious threats to the Earth such as near-Earth objects and other imminent dangers.

### 5.1.2 Economic

Economic considerations will contribute to the policy debates and ultimately provide the financial impetus for following through with the mission. Sound arguments demonstrating a clear cost benefit analysis and return to the overall well-being of a nation's economy including job creation, benefits to the industrial base, commercialization and incentives for private investors will be important to make.

Tying into the previous political discussion, the facilitation of an international coalition can only occur if participating countries ensure that the legal path is clear

and streamlined to foster industry and government participation. Favorable projected returns will likely create an impetus for greater political capital to support Luna Gaia. However, numerous hurdles stand in the way of private involvement. For this reason, policy issues relating to incorporating the private sector will be discussed. The critical areas that should be resolved or addressed include property rights for private partners and export controls including ITAR; both are discussed in the report.

### **5.1.3 Scientific**

Conducting scientific experiments and enhancing our understanding of the universe are part of the core mission requirements for the Luna Gaia habitat. Scientific discovery will undoubtedly provide benefits to mankind; however, policy-makers will seek to define the boundaries of scientific and technological research that may be realized. Some major policy decisions relating to planetary protection for monitoring contamination of Earth and Moon resources as well as the use of nuclear power will be discussed in Sections 5.5 and 5.6 respectively. There are also ethical issues relating to the types of research that may be conducted on the lunar settlement included in the Ethics Section (Section 4.2) of the report.

### **5.1.4 Societal**

A more philosophical public discussion should also ensue to address the role of government and industry. This forum will address the necessary governance, ethics, and legality of private and public activities on the Moon. Mankind has a responsibility to preserve and protect its environment, and should seek to strive for a code of conduct that constructively engages and respects the lunar environment. The societal drivers are discussed in greater detail in Chapter 4 Philosophical and Societal Issues. These remain important facilitators and contributors to the policy debates that must precede the inauguration of Luna Gaia.

### **5.1.5 Critical Path for Policy**

As the confluence of policy drivers and ethical dilemmas emerge four key areas of contention likely to be in the forefront of public and private debates regarding the feasibility of Luna Gaia. These issues have been identified as being on the “critical policy path”:

- Governing Body
- Incorporating the Private Sector
- Planetary protection
- Nuclear power

## **5.2 Governing Body**

Although outside of the scope of the project, a discussion relating to the types of governing bodies and oversight needed for a lunar settlement will have to be assessed in greater detail. For this report, we have incorporated some preliminary ideas and concepts to provide future guidance to policy-makers.

From a top level perspective, the political questions that must be answered involve determining the necessary framework to enable international participation. The governing body on Earth and the one established for the Moon will play an important role in creating this endeavor. This governing body should be international and financially cooperative, should map out a framework for enabling negotiations (internal and external) and conflict resolution, and should also regulate lunar activities. Admittedly a challenge, the establishment of a Luna Gaia

intergovernmental agreement will be critical to long-term mission success and provides for a sustained settlement.

### **5.2.1 Governing Models**

This project considered several frameworks when selecting a forward strategy for the development of a governing body for Luna Gaia (Zelnio, 2006b). These include framework approaches based on project coordination, augmentation, interdependency, and integration as described below.

The coordination approach consists of each state maintaining a separate lunar base with some level of coordination between the other lunar bases. This model was recommended against because of redundancies and inefficiencies that would occur through a separate development of the modules.

Under the augmentation approach, one country leads the lunar base effort and other states contribute non-critical components and thus are never in the critical path. This is not an optimal approach because it does not give all of the space-faring nations the proper level of participation or influence. It also relies too heavily on one player who could drastically deviate from the original plan.

The interdependency model allows for multiple states to be on a shared critical path and depend on each other. However this paradigm does not easily allow for an overseeing/governing body and rather relies on states to act in good faith, determined heavily by acts of reciprocity.

The integration model is optimal because there is complete cooperation among the parties and funding issues are managed by a central entity. While this model is useful in theory, every partner is dependant on the others, with little financial accountability established among them. Thus, terms of agreement for accountability and appropriate recourse need to be carefully analyzed before such a model is adopted. An example of this model is the European Space Agency, which should be assessed as a basic skeleton for a broader Luna Gaia Agreement.

### **5.2.2 Recommendations**

Because of the relatively novel nature of the governing body, recommendations for its implementation and use will be provided as guidelines. These include:

*Lessons learned from the International Space Station:* In determining the overall best framework for a Luna Gaia governing body, lessons learned from the ISS project should be taken into consideration. These include putting in place a regime that will make states accountable for their technical contributions and for enforcing financial commitments. Benefits of the ISS system include having redundancy of transport systems, which could be useful in the construction of Luna Gaia as well (David, 2000).

*Creation of an international space agency:* We recommend the creation of an International Space Exploration Agency (ISEA) to facilitate work between the different states. The creation of a new space agency whose mission is to unify states in the exploration of space will provide the framework necessary for sustainable and efficient international cooperation. This agency would enable an integrated program which would lead to more efficient sharing of costs while reducing duplication of effort in research and development, design, production, and exploration. There would be full cooperation between states, and the funding would be managed independently by the central entity, ISEA, to the advantage of all states.

The ISEA should also craft agreements between states on issues such as diplomacy, negotiations, state-to-state reciprocity, and dealing with conflict on matters involving the lunar settlement. At the state level, it will be important for all participating nations to have a clear understanding of the vision and to have the participants vested in the sustainability of the mission. The states should also come to an agreement on the level of lunar environmental protection and the level of transparency among participating members. This agency could be established as an independent body, an affiliate of an already standing international organization like the U.N., or through multilateral agreements established by the participating states.

*Global Security Cooperation:* Although the use of outer space is reserved for peaceful purposes based on the Outer Space Treaty, an international military coalition in conjunction with the Luna Gaia scientists could be created in the event of a catastrophic threat to Earth. This would include the monitoring of near-Earth objects in a collaborative manner. In the event action is necessary to mitigate a threat, the rules provided for international engagement via the Luna Gaia Agreement would be implemented.

### **5.3 Paving the Path for Private Involvement**

The establishment of a lunar base will undoubtedly raise concerns of cost burden sharing and mandate an assessment of economic returns. While governments and participants of the lunar settlement may choose to attempt it alone, it seems highly unlikely given the political climate of this day and age. More than ever, domestic pressures and competition for funds force governments to cut or scale back space programs to give way for “higher priority” items. In the United States, for example, consistent pressure to terminate or decrease funds for ISS led to erratic government contributions, fiscal waste, and unfulfilled promises. Thus public pressure to find alternative sources of funding is real.

This will also be a crux argument for decision-makers looking for industry to share in the costs and develop the systems more efficiently. In order to seek industry input and optimize risk, there are a few regulatory hurdles that must be resolved in order to incorporate private funding streams. The major ones highlighted in this report include the issue of property rights and export controls, with a specific focus on ITAR.

#### **5.3.1 Property Rights**

The current debates on commercialization and property rights issues for private entities on the Moon are divergent and remain relatively nebulous due to the lack of specific legal regimes in place. Many of the provisions of the Outer Space Treaty allow for the creation of a self-sustained lunar base such as Luna Gaia. However, most of these guidelines are written in a very subjective language which could easily be interpreted to a state's advantage. For instance, a key argument against property rights hinges on the Outer Space Treaty, which prohibits states from establishing territorial sovereignty. While no specific mention of commercial entities is mentioned at all, the treaty does go on to postulate that in some cases, states are required to exercise jurisdiction and control over space objects and personnel.

In fact, attempts in the opposite direction have been made by governments to prohibit property rights. The 1979 Moon Treaty provides a basis for development while prohibiting real property rights the core reason twelve nations ratified the treaty. Article VI of the treaty, for example, allows the use of mineral and other

resources of the Moon in quantities appropriate for the support of their missions. However, this does not provide enough leverage or deeds for re-sale on Earth. Private investors and other non-governmental entities have repeatedly emphasized the need for property rights protection to effectively forge a relationship with governments. In order to enable a framework for property rights, a few precedents will be analyzed to provide broader perspective on the matter.

### *Past and Present: Determining Property Rights*

Examples of successful and unsuccessful forays into determining property rights include the case studies of American expansionism and the treaties on Antarctica and the Law of the Sea. In the American West, private property rights and land giveaways occurred through the Homesteading Acts, guaranteeing expansion. This model could be an interesting one since it required owners to maintain a facility in a fixed location for specific amount of time to establish a property right. Similar regimes were established for Alaska since there were mineral rights and ensuing property rights in order to attract investors and large mining corporations (White, 1997). In contrast, the Antarctic Treaty denies property rights, so only scientific work can be realized. After many years of scientific governmental collaboration in Antarctica, there is still no growing infrastructure or development. While this may be an acceptable model for scientific collaboration, it does not provide for a solid paradigm to incorporate private investors.

The Law of the Sea Treaty is similar to the Moon Treaty in that it provided for a governing regime that oversees the appropriation of ocean resources. Major countries such as the U.S. were unwilling to ratify the Sea Treaty and instead offered an alternative regime called the “Deep Seabed Hard Resources Act” which was intended to oversee mining activity until a new international treaty was agreed upon. This act, of which parts could be adapted for future missions on the Moon, provided for renewable permits to ensure tenure of mining sites with respect to international entities including a “denial of extraterritorial sovereignty” (1982) Thus, precedents for sharing “common resources” exist in practice.

### *Enabling Property Rights*

Commercial interest is growing for lunar resources such as water, oxygen, and hydrogen as well as for building materials like, titanium, magnesium concrete made of regolith and other structural materials. For example, the lunar silicon could be utilized for producing photovoltaic cells as well as electronics. As commercialization opportunities become reality, a new legal regime will be needed to allow for profiting from these resources and for cooperation on an international level. Cooperation could take place in terms of both national and corporate ventures. As discussed previously, the Outer Space Treaty allows the freedom to use space resources. However, it mandates using the concept of benefit sharing and non-appropriation. The Moon Treaty also discourages commercialization, however, is not considered a binding agreement. Private entities need legal certainty about property rights before investing their money in space activities.

Our recommendations are to call for a clear-cut property rights regime that encourages and secures private investment in the future. These recommendations present two basic concepts, with one principle that should be incorporated into both concepts. The first and less preferable concept is to modify the Moon Agreement. The second is to pave the way for a new document. Finally, principles should be incorporated in either proposal that allow for the participation of smaller, non-space faring nations that may not have the capabilities to develop areas of the Moon.

Modification of the Moon Treaty: There are legal interpretations for Article 11 of the Moon Treaty that effectively allow for property rights as long as they are not eternal. This interpretation relies on a first-come, first-served basis occupation with a treaty prohibition against harmful interference of other states' activities (White, 1997). Once a state abandons the settlement, it would be open for a different state to occupy the land. This functional property rights regime would also be extended to non-governmental entities. Commercial entities may choose to participate through functional property rights regime; however, since this is not explicitly stated in the Moon Agreement, significant risk would still have to be accepted by industry players. While amending the Moon Agreement has not been a popular option in past discussions, some amendments to its text could provide the impetus to re-start negotiations. Furthermore, since the agreement already exists, a foundation from which to start is already granted.

#### *Development of a New Framework Agreement:*

Developing a new framework would prove challenging and may not yield the necessary results in the end. However, there are benefits to starting over, especially when one takes into consideration some of the previous disagreements from the Moon Agreement. A suggestion that may be further explored is the bestowal of a title/deed that would not be dependent upon government control or sovereignty of an area but rather over its control of personnel and any systems on the settlement (White, 1997). Functional property rights would be restricted by Article VIII of the Outer Space Treaty and would effectively terminate if a base or space object were abandoned. Rights would also have to be restricted to a confined area based on the occupation, movement and relative safety of the claimed area. An alternative construct may be to incorporate a similar agreement to the Homesteading Acts (1862), which would grant eventual permanent property rights after a fixed time of development and presence in the area.

*Principle of Inclusion:* Within both recommended constructs, allotments should be made to enable less economically developed countries access to property rights on the Moon, despite inability to launch there. The core reasoning behind including such a principle is to maintain the spirit of “access for all mankind” but also in order to ensure that a chosen few are not the only ones capable of obtaining property rights. Furthermore, a multi-lateral agreement would be unlikely without such a stipulation.

This regime could be implemented in a number of ways including: enabling non-spacefaring nation's access to territory or old installations after they are abandoned, granting opportunities for sub-contracting and payment through “equity share plans” to enable inclusion and the allowance for the re-sale of some of the resources in their countries without prohibitive tariffs. Another possibility is to implement a system that is modeled after the distribution of geostationary orbital slots by the International Telecommunications Union. A “first-come, first-served” principle would still be allowed for contributing nations and investors; however, parallel opportunities to gain access to lunar resources for lesser-developed countries should be carefully considered as well.

## **5.4 Export Controls Regulations**

One major hurdle identified repeatedly by private corporations threatening international cooperation is the use of export controls, and in particular ITAR. While this is a U.S. based export control, it has had and will continue to have broader implications for global cooperation. Without some form of export control and specifically ITAR reform, industry will be wary of contributing to the



international coalition necessary to build Luna Gaia. Therefore, a brief discussion of the policy issues involving export controls is warranted.

### **5.4.1 Export Control Regimes**

Export controls are handled at the international, regional and national levels. At the international level, they rely on the political will of signatory regimes to implement the principles in their legislations. Examples include the Missile Technology Control Regime (MTCR) and the Wassenaar Agreement. While these political documents lack any legal recourse, they provide a common basis for which national legislation might be based (Project, 2006). Export control agreements at the regional level define special cases of control and exemptions within the partner states. It is at the national level, however, that technologies are identified for transfer restrictions and the export control legislation is created and in turn governs the licensing agreements.

The primary question is what technology will be restricted by export control legislation. A general answer is that technologies with military origins, developed through the utilization of military derived technology or items that could be included in military components are subject to export controls (Project, 2006). In addition, it is frequently difficult to exchange data, develop compatible component parts together, and cooperate at a level of transparency necessary for success.

### **5.4.2 Example: ITAR**

The space industry is highly influenced by export control legislations because of the technologies used and inherent “dual use” nature of the space industry. The restriction of the technology transfer posed by export control legislations contradicts international corporations for scientific missions in outer space. An example of national level export control is the U.S. International Traffic in Arms Regulations (ITAR) that controls the permanent and temporary export and temporary import of defense articles and services. Since ITAR controls the export of weapons technologies overseas, it is essential for U.S. national security. However, it makes participation of the U.S. in international space missions difficult due to classification of spacecraft systems and associated equipment as munitions items. It also makes cooperating with the U.S. as an international partner extremely tedious when building assemblies for the project in other partner countries, procuring and managing the flow of parts for those assemblies and managing the flow of documentation associated with them (State, 2006).

ITAR places restrictions on the transfer of high technology and items of a military nature that are subject to export control concerns at different international and national levels. The primary rationale for imposing these controls is for protecting the geopolitical, strategic and economic advantages of the United States. However, there have been numerous negative consequences that have emerged as a result including the discouragement of international collaboration, suppression of competition, and denial of valuable and helpful knowledge gain through emergent technologies. Numerous items on the ITAR munitions lists, for example, bar the use of certain parts to enable the construction of a satellite. In fact, the US satellite industry has experienced a precipitous decline in market share as a result (Zelnio, 2006a). Other programs, such as the jointly led US-UK Joint Strike Fighter Program has been frequently delayed and threatened for termination due to ITAR restrictions (daily, 2005).

### **5.4.3 Recommendations**

Export control issues will be challenging for an international lunar-based habitat. Without some type of export control reform and in particular, ITAR reform, the

likelihood for international cooperation diminishes. For this reason, recommendations are warranted to provide constructive means of fine-tuning the treaty while engaging partners for mission success. Some recommendations to solve these issues include (Szoka, 2006):

*Making distinctions between end users:* This means allowing traditional allies and close international partners greater access and transparency for project development and trade, while maintaining strict regulations against potentially unfriendly states (Szoka, 2006).

*Offer different levels of regulations to cooperating states:* Essentially, providing MOUs and other bilateral agreements between states regarding technology transfer and exceptions for collaborative efforts.

*Reforming munitions lists:* These types of lists (especially ITAR) are extremely contentious and could be reformed to allow for spacecraft systems and associated equipment.

## 5.5 Planetary Protection

Pursuant to the political and scientific policy drivers enabling scientific experimentation, a lunar base will afford a remote location for the study of materials from extra-terrestrial bodies with potential for bearing alien specimens and life. The 1967 Outer Space Treaty notes that all states party to the treaty "shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination." In light of this, determining the appropriate mechanisms for planetary protection will be a driver of immediate interest.

Planetary protection is the practice of protecting celestial bodies from contamination, specifically related to astrobiology missions including both forward and backward contamination. Contamination is defined as the uncontrolled or uncataloged transfer of biological material, potential life forms, or other potentially hazardous substances. An overview of potential sources of contamination, with recommendations for protocols, technological procedures, and standards can be found in Section 3.5, Safety.

Forward contamination refers to the transport from Earth to a celestial body and backward to the transport from the celestial body back to Earth. Planetary protection is essential for studying other worlds in an undisturbed state, to avoid obscuring our ability to find life elsewhere, and to take precautions to protect Earth's biosphere in case we find life on another celestial body.

Within this context, two areas arise: Using the Moon for scientific research, and contamination of the lunar environment with nuclear waste. In fact, using the Moon as a location for scientific research should not conflict with the international treaties; in effect, it would likely facilitate agreement between international partners since participating nations would likely agree that conducting these tests and experiments on the Moon are preferable to landing extraterrestrial substances in one particular state.

The nuclear reactor baselined for power supply (see Section 2.3, Power) raises the issue of contamination of the lunar surface with nuclear waste. Here COSPAR planetary protection policy is insufficient and international agreements do not exist. An international policy addressing the contamination of celestial objects with nuclear waste will have to be established.

### **5.5.1 Quarantine of Martian Samples**

Following the 1996 announcement by NASA scientists of possible evidence of past life in the Martian meteorite ALH8001, NASA implemented more stringent procedures regarding planetary protection. One of the arguments put forward is that as more and more states gain access to space, international guidelines and enforcement mechanisms may become necessary in order to ensure planetary protection. A protocol should therefore be developed for detection of life and biohazards and a strategy for quarantine and distribution of samples, drawing from existing protocols such as COSPAR guidelines, The Quarantine and Certification of Martian Samples (Kaiser, 2006), and standards adopted by the International Council for Scientific Unions (ICSU).

### **5.5.2 Recommendations**

We recommend using the current policy and guidelines of COSPAR that denotes policies and protocols for planetary protection. The general policy states that the conduct of scientific investigations of possible extraterrestrial life forms, precursors, and remnants should not be jeopardized. In addition, the Earth must be protected from the potential hazard posed by extraterrestrial matter carried by spacecraft returning from another planet. Therefore, for certain space mission/target planet combinations, controls on contamination shall be imposed in accordance with issuances implementing this policy.

- We recommend that an international agreement for planetary protection be created, signed and ratified by all international partners. An advisory panel of experts should be created to coordinate regulatory responsibilities and an administrative structure should be established within the Luna Gaia development team. This panel would verify and certify adherence to planetary protection requirements at each critical stage of a sample-return mission, including launch, reentry and sample distribution.
- We recommend a careful assessment of existing legislation and to pursue the establishment of international standards that will safeguard the scientific integrity of research on the Moon, and Mars as well as providing protection for Earth and her inhabitants. Throughout the sample return program, every effort should be made to inform the public of current planetary protection plans and provide continuing updates regarding exploration and sample returns.
- Finally, within the technical proposal of the report, the Luna Gaia design team recommends the construction of a contamination containment module that is safe and quarantined from the rest of the living and working quarters. This module would serve as the first foray to human contact for extraterrestrial specimens in accordance with international planetary protection regulations.

## **5.6 Nuclear Power**

When determining feasible and cost-effective energy sources for Luna Gaia, it became apparent that nuclear power will be seriously considered as an energy source for the lunar base. Although other alternatives exist and are considered in the report (including photovoltaic and solar thermal power), small nuclear reactors are necessary at least in the short-term due to the cost, mass, and efficiency ratios they provide vis a vis other options. With the baselined nuclear power being on the critical path for Luna Gaia development, it is necessary to review the major policy

issues facing nuclear power and determine proactive measures that can alleviate the fears and concerns over its use.

Numerous policy issues, however, could potentially provide serious barriers to enabling this power source on the Moon. These major unresolved problems include perceived danger of the technology, environmental and health effects, potential security risks stemming from proliferation and challenges in the long-term management of nuclear waste (MIT, 2003).

### **5.6.1 Adverse Safety, Environmental, and Health Risks**

The use of nuclear energy power sources for human spaceflight and settlement creates concern among many political actors on the safety and reliability of these technologies for human health on Earth and outside our Planet. These safety issues must be addressed and mitigated before proceeding forward. The adverse effects of and protection measures for nuclear radiation are discussed in Section 3.4, Radiation of the report.

### **5.6.2 Potential Security Risks**

As it clearly states in Article IV of the Outer Space Treaty, nuclear technologies in space and other planetary bodies must be used exclusively for peaceful non-aggressive purposes. This includes prohibiting the placing of weapons of mass destruction in orbit or on any celestial bodies. It will therefore be incumbent upon all of the participating nations to pledge their agreement to use nuclear power for peaceful purposes only.

However, it is important to note that the peaceful purposes clause does not exclude the use of military resources and personnel: “The use of military personnel for scientific research or for any other peaceful purposes shall not be prohibited. The use of any equipment or facility necessary for peaceful exploration of the Moon and other celestial bodies shall also not be prohibited.” Given the varied parameters, the effectiveness of these important provisions rely on the good will and faith of the State parties. Therefore carefully outlining and reinforcing these provisions will be critical for inter-governmental cooperation.

### **5.6.3 Nuclear Waste**

The issue of nuclear waste will be significant not only for safeguarding the lunar environment, but also for maintaining the health and safety of the future inhabitants. Regarding nuclear waste, the United Nations General Assembly approved a non-binding declaration called “Principles Relevant to the Use of Nuclear Power Sources in Outer Space” where it acknowledges the need to ensure the safe use and disposal of nuclear power. While not binding under international public law, this GA Resolution provides future users of nuclear powers sources in space with useful guidelines and a general framework of action, management, and safe use (Holt, 2006). Policy-makers will undoubtedly be called upon to make further assessments and eventually issue an appropriate protocol for safe nuclear waste disposal before nuclear power may be used on Luna Gaia.

---

# Legal Issues

## 6.1 Legal Framework

Today's space activities are adequately covered under the existing legal framework; however to accommodate space activities that have an element of commercialization, the existing regime will require revisions. This current state of affairs makes the identification of the legal framework for Luna Gaia a challenge. In this section, we examine the existing legal framework, identify the applicable principles and bring to light the discrepancies and gaps in the context of building a habitat for humans on the Moon. The policy chapter explores our recommended changes to existing space law to build a framework that promotes more commercial activity.

### 6.1.1 Existing Legal Framework

The existing international public space law for space activities consists of the following 5 treaties and 5 resolutions of the UN General Assembly (UNGA).

The 5 treaties are:

- The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies ("The Outer space Treaty") 1967
- The Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space ("The Rescue Agreement") 1968
- The Convention on International Liability for Damage Caused by Space Objects ("The Liability Convention") 1972
- The Convention on Registration of Objects Launched into Outer Space ("The Registration Convention") 1975
- The Agreement Governing the Activities of States on the Moon and Other Celestial Bodies ("The Moon Agreement") 1979

The 5 resolutions are:

- The Declaration of Legal Principles Governing the Activities of States in the Exploration and Uses of Outer Space (General Assembly resolution 1962 (XVIII) of 13 December 1963)
- The Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting (resolution 37/92 of 10 December 1982)
- The Principles Relating to Remote Sensing of the Earth from Outer Space (resolution 41/65 of 3 December 1986)
- The Principles Relevant to the Use of Nuclear Power Sources in Outer Space (resolution 47/68 of 14 December 1992)
- The Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States,

Taking into Particular Account the Needs of Developing Countries  
(resolution 51/122 of 13 December 1996)

## **6.2 Obsolescence of The Moon Agreement**

Space law relating to the human activities on the Moon does exist in both the Outer Space Treaty and the Moon Agreement. As of 1 January 2006, 98 states have ratified the Outer Space Treaty, but only 12 states ratified the Moon Agreement. Moreover, the major space faring nations capable of independent access to space (e.g.: Russia, United States of America, and China) have not ratified the Moon Agreement.

The most contentious points relate to the provisions of Article 11 of the Moon Agreement as follows:

- Role of developing countries under the Moon Agreement
- Non-appropriation (property rights) for non-governmental entities.

If private companies are willing to participate and invest capital in the Luna Gaia project then they should be allowed to gain profit from their activities on the Moon. We propose to add a protocol to the Outer Space Treaty and revise the Moon Agreement with respect to the articles concerning private property rights (Kosuge, 2005). In fact, commercial activities are allowed in the current Moon Agreement. According to Article XI of the Moon Agreement, an international regime (or authority) has to be established under the auspices of the United Nations. This international authority or regime will regulate lunar commercial activities and exploitation of lunar resources. Sharing of profits between private and public partners as well as developing countries would also be covered by this authority. See Section 5 Policy for further discussion of property rights.

We shall respect the principles of non-appropriation and benefit to mankind at the center of the Luna Gaia project. However, if the policy drivers are strong enough, there is a possibility through the use of agreements or additional protocols to allow private entities the profitable commercial use and development of lunar resources without crossing the line into appropriation.

## **6.3 Examination of International Space Station Legal Framework**

The ISS is the only available large scale, long duration manned mission in outer space regulated through intergovernmental cooperation. Therefore it is the reference in analyzing legal issues and legal framework related to Luna Gaia (Table 6.4-1). The ISS regime is described in the Intergovernmental Agreement (IGA), which was originally designed as a cooperative project between ESA member states, Russia, Canada, Japan and the United States of America. The ISS is developed, operated, and utilized in accordance with international law, including the Outer Space Treaty, the Rescue Agreement, the Liability Convention, and the Registration Convention (IGA Article 2). In addition, the IGA includes provisions for criminal jurisdiction, intellectual property, utilization rights for launched objects, and astronauts' activities on the ISS. It has provisions for cross-waivers of liability, exchange of data and goods, customs and immigration, and consultation to achieve smooth international cooperation on the Earth relating to the ISS activity. As a precursor document to the Luna Gaia agreement discussed later in this section, the IGA states that activities are deemed to have occurred only in the territory of the partner state of that element's registry. By this logic, each ISS flight element is an independent structure, and partners are required to register the

structural elements they provide. In the case of the proposed lunar settlement, liability and responsibility are likely to be decided by the state of registry since registration regulates jurisdiction and control (Takizawa, 1987). Determining the relationship between the states of registry is therefore crucial to the Luna Gaia habitat.

**Table 6.4-1 Luna Gaia Legal Issues (Compared with IGA)**

Topics	International Space Station Intergovernmental Agreement (IGA)	Existing Space Law	Legal Issues and Recommendations for ISEA or Luna Gaia Agreement
<b>Management</b>	Accordance with international law <i>IGA Article 2</i>	Accordance with international law <i>OST Article 3</i> <i>MA Article 2</i>	Same as IGA and Existing Space Law
	Management by ISS Partners <i>IGA Article 7</i>	The principle of cooperation and mutual assistance <i>OST Article 9</i> <i>MA Article 4</i>	Same as Existing Space Law
<b>Activities</b>		Freedom of use <i>OST Article 1</i>	Same as Existing Space Law
	Defines who designs and develops elements / partners have the right to access the ISS <i>IGA Article 8</i> <i>IGA Article 12</i>		Same as IGA
		Freedom to establish manned and unmanned stations <i>MA Article 8</i>	Same as Existing Space Law
		Benefit for all countries <i>OST Article 1</i> <i>MA Article 4</i>	Same as Existing Space Law
		No militarization <i>OST Article 4</i> <i>MA Article 3</i>	Same as Existing Space Law

Topics	International Space Station Intergovernmental Agreement (IGA)	Existing Space Law	Legal Issues and Recommendations for ISEA or Luna Gaia Agreement
		Necessity of establishing an international regime for exploitation of the natural resources of the Moon <i>MA Article 11</i>	Same as Existing Space Law
<b>Budget</b>	Defines each party's financial obligations <i>IGA Article 15</i>		Same as IGA
<b>Registration</b>	State of registry is the state which provide the flight elements <i>IGA Article 5</i>	State of registry should be state which provides the flight elements. In the case of multiple states developing one flight element, one state should be designated as the state of registry <i>RC Article 2</i>	Same as Existing Space Law
<b>Jurisdiction and Control</b>	Retained jurisdiction and control by the state of registry <i>IGA Article 5</i>	Retained jurisdiction and control by the state of registry <i>OST Article 8</i> <i>MA Article 12</i>	Same as Existing Space Law
<b>Ownership</b>		No ownership of subsurface of the Moon nor any part thereof, including natural resources <i>MA Article 11</i>  Non appropriation <i>OST Article 2</i> <i>MA Article 11</i>	If the policy drivers are strong enough, the use of agreements or additional protocols could allow private entities the profitable commercial use and development of lunar resources without appropriation



Topics	International Space Station Intergovernmental Agreement (IGA)	Existing Space Law	Legal Issues and Recommendations for ISEA or Luna Gaia Agreement
	Maintain ownership of objects launched <i>IGA Article 6</i>	Maintain ownership of objects launched to the Moon or into outer space <i>OST Article 8</i> <i>MA Article 12</i>	Same as Existing Space Law
<b>Utilization Rights</b>	Acquisition of utilization rights <i>IGA Article 9</i>		States and private entities shall maintain utilization rights of objects launched to the Moon
<b>Operations</b>	States should be responsible for the operation of the elements they respectively provide <i>IGA Article 10</i>		Participating entity should be responsible for the operation of the elements they respectively provide
<b>Crew</b>	The Code of Conduct for the Space Station crew <i>IGA Article 11</i>	Crew of Luna Gaia are astronauts <i>OST Article 5</i> <i>MA Article 10</i>	Same as IGA and Existing Space Law
<b>Risk management</b>	Cross-waiver of liability by the partner states and related entities <i>IGA Article 16</i>		Same as IGA
<b>Liability</b>	Accordance with the Liability Convention <i>IGA Article 17</i>	The launching state at fault is liable for damage on the surface of Moon <i>LC Article 3</i>	Same as Existing Space Law
		The participants in a joint launching may conclude agreements about financial obligations <i>LC Article 5</i>	Joint liability under ISEA
<b>Supervision of Non-Governmental Activity</b>		Supervision by appropriate states <i>OST Article 6</i>	Same as Existing Space Law

Topics	International Space Station Intergovernmental Agreement (IGA)	Existing Space Law	Legal Issues and Recommendations for ISEA or Luna Gaia Agreement
		<i>MA Article 14</i>	
<b>Exchange of Data and Goods</b>	All technical data and goods which are needed shall be transferred to the partners <i>IGA Article 19</i>		All technical data and goods which are needed shall transfer to partners
<b>Intellectual Property</b>	Intellectual properties are deemed to have originated in partner state of that element's registry <i>IGA Article 21</i>		Same as IGA
<b>Customs and Freedom of Movement</b>	Facilitated immigration and duty free <i>IGA Article 18</i>		Customs should be duty free and freedom of movement should be facilitated
<b>Contamination Prevention</b>		Obligation to prevent contamination <i>OST Article 9</i> <i>MA Article 7</i>	Same as Existing Space Law
<b>Criminal Jurisdiction</b>	Criminal jurisdiction over personnel in or on any flight element who are their respective nationals <i>IGA Article 22</i>		Same as IGA
<b>Consultations</b>	Consult each other <i>IGA Article 23</i>		Same as IGA
<b>Dual Use</b>			Promote dual use technology through an internationally accepted frame

## 6.4 Luna Gaia's Legal Framework

Assuming a regulating body such as the International Space Exploration Agency (ISEA) concept introduced in Section 5 is established, it should be formed based on the United Nations Vienna Convention on the Law of Treaties (1969). An initiative such as ISEA would raise some challenges related to the nature of space activities such as cost, national security requirements, and competition. Other concerns would relate to politics, particularly the different views of developing and developed nations. However, a new agency of this type can implement assistance for developing countries and also coordinate actions that are currently conducted in a disorderly fashion. The purpose of ISEA should be comprehensive for all cooperating states on issues like the use of the Moon for scientific purposes only or putting large space stations into orbit.

The ISEA’s mission should first be confined to the tasks that can be undertaken within its operating scope. The ISEA should pursue the following goals:

- Promoting the Luna Gaia habitat and its lunar exploration mission
- Ensuring that international responsibility is jointly vested between ISEA and its member states
- Encouraging the transfer of space technologies to developing countries to expand their space activities (Crowther, 1998)
- Promoting dual use technology through an internationally accepted framework.

Because it will take a long time to establish such an organization, it would be realistic from the legal point of view to implement and execute the Luna Gaia project by means of cooperation between intergovernmental and private companies, while using existing space law until a body like ISEA is established. The legal framework that we recommend for Luna Gaia before the establishment of ISEA is illustrated in Figure 6.4-1.

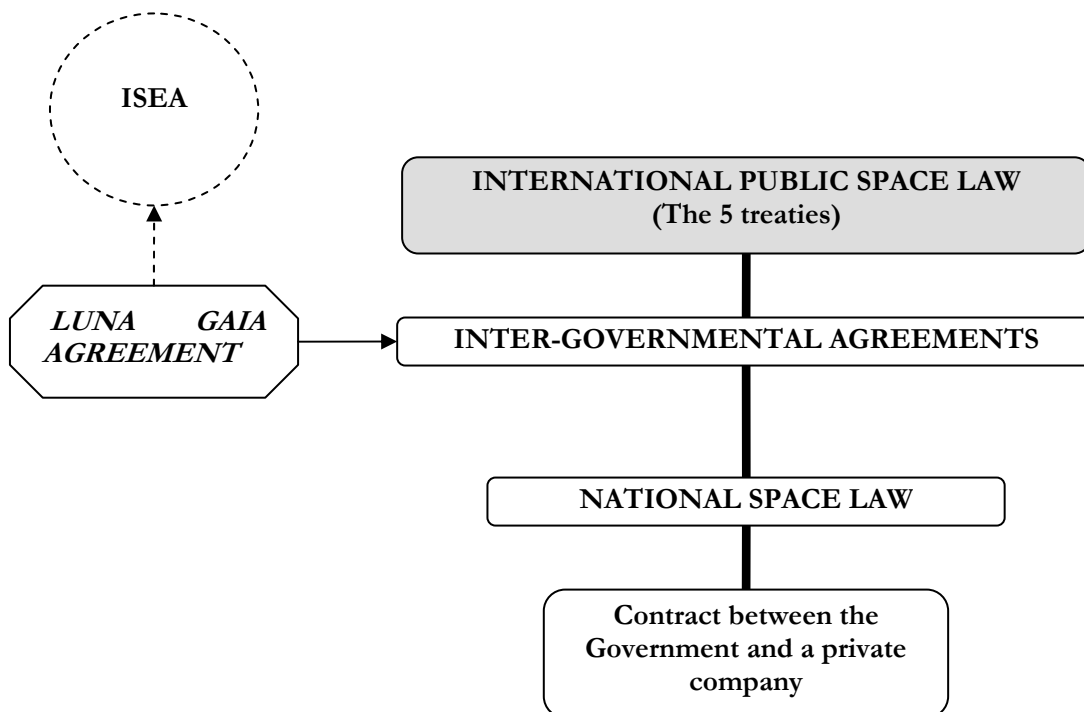


Figure 6.4-1 Luna Gaia’s Legal Framework

### 6.4.1 Inter-Governmental Cooperation

The Lunar habitat discussed in this document will be the product of intergovernmental cooperation. As such, an intergovernmental agreement regulating the habitat is strongly needed, because Intergovernmental activities on the Earth should facilitate and maintain the proposed project. We recommend defining a budget, purchasing insurance, exercising cross-waivers of liability, establishing third-party liability, regulating private companies’ activities, and establishing jurisdiction and control. In particular, jurisdiction and control relates to governance of the habitat and the provisions regarding the states of registry. We mentioned earlier in this section the importance of the state of registry to the operation of the habitat. According to the Registration Convention, the State of Registry has been defined as ‘a launching state whose registry of a space object is carried’ in accordance with Article II. By this definition, there may be only one state of registry per space object (module or component). In the event that there

are several launching states, they must determine which one of them will register the object in its national registry. These states may further agree on the application of certain aspects of the legislation of the chosen state of registry. The Registration Convention allows launching states to conclude agreements on jurisdiction and control over the space object of interest. Thus, launching states can decide to transfer certain jurisdictional rights to others, such as in case of criminal law under the Intergovernmental Agreement of the International Space Station (Hermida, 2004).

#### **6.4.2 Cooperation Between Governments and Other Partners**

Many types of entities have engaged in outer space activities in the last decades. These include mixed companies held by private shareholders and the government, research institutes from state-owned universities, commercial companies whose sole shareholder is the state or a state agency, and international consortia made of states, private companies, and mixed entities. Cooperation means that contracts regulating space law, national law, intellectual property, and general cooperation among governments and other partners will be required (Hermida, 2004). The distribution of a private company's profits under the principles of the Outer Space Treaty and the Moon Agreement would also be covered in this contract. Article VI of the Outer Space Treaty states that the activities of non-governmental entities in outer space, including the Moon and other celestial bodies, will require authorization and continuing supervision by the appropriate state. Private companies may not directly make a claim against a launching state under the Liability Convention. The Liability Convention also allows special arrangements between states to redistribute their financial obligations, such as the liability regime adopted for the ISS. These agreements are valid only among these states and not for non-participating states (Hermida, 2004).

#### **6.4.3 Contamination and Pollution**

Nuclear power sources have been used for the purpose of generating energy for space objects. While this may be regarded as a useful achievement, it has all the risks inherent to nuclear fission on Earth, but with the added risks associated with the space environment (Vershoor, 1999). In the sphere of contamination and pollution hazards, due diligence must be paid to Article IX of the Outer Space Treaty and Article 7 the Moon Agreement. These articles state that the studies must be pursued and exploration activities conducted in such a way as to avoid harmful contamination of outer space, and also adverse changes to the environment of Earth resulting from the introduction of extraterrestrial matters. Under current space law, there is no limitation to the use of nuclear power sources as long as it is for peaceful and scientific purpose and does not result in direct harmful contamination of outer space, the Moon, celestial bodies, or Earth (Vershoor, 1999). Legally speaking, our recommendation regarding using nuclear power sources for the lunar habitat is to produce guidelines and specifications for the safe use of nuclear power and disposal of waste. It has to be stressed that in order to minimize the quantity of radioactive material in space and the risks involved, the use of nuclear power sources in outer space shall be restricted to those space missions which cannot be operated by non-nuclear energy sources in a reasonable way as recommended by consensus in UNCOPUOS (United Nations Committee on the Peaceful Uses of Outer Space) in 1991. Consistently with this stipulation, the lunar habitat is planned to be progressively less dependent on nuclear energy and eventually not need it at all. This will be made possible once an equivalent source of power such as solar thermal power is proven and fully operational (Solar thermal power described in Section 2.3, Power). Ethical and

policy-related considerations are addressed in Section 4.2 Ethics, and Section 5 Policy (Vershoor, 1999).

#### **6.4.4 Conclusions and Recommendations**

Space law relating to the human activities on the Moon exists, but is insufficient for sustainable lunar exploration. If private companies are willing to participate and invest capital in the Luna Gaia project then we need to revise or amend the Moon Agreement. But we have to keep the principles of non-appropriation and benefit to mankind at the center of the Luna Gaia project.

Assuming a regulating body such as the International Space Exploration Agency (ISEA) concept is established in Luna Gaia, it should be formed based on the United Nations Vienna Convention on the Law of Treaties (1969). Since it will likely take a long time to establish such an organization, it would be more realistic to implement and execute the Luna Gaia project using existing space law by means of cooperation between intergovernmental and private companies until a body like ISEA is established. It is clear that an intergovernmental agreement relating the habitat is strongly needed, because intergovernmental activities on Earth should facilitate and maintain the proposed project.



---

# Economic Issues

## 7.1 Budget

### 7.1.1 Introduction

A careful assessment of the international budgetary environment for space programs will assist in the understanding of the opportunities and constraints to develop a strategy to finance the lunar base. Garnering the political and monetary support for an artificial environment will likely require an international, public-private partnership (PPP) effort due to the projected magnitude and costs of such an undertaking. This conclusion is based on an assessment of available funding for space programs which typically encounter numerous constraints and competing priorities from domestic and international initiatives. Thus, public and private financing will have to be incorporated in order to ensure long-term monetary support.

The project team undertook a *preliminary* budgetary assessment in order to gauge orders of magnitude and a proximal range for cost. An in-depth cost analysis is essential to guard against sub-standard costing methods that could lead to miscalculations and subsequent cost-overruns threatening mission viability.

When devising a cost model for an international partnership, numerous considerations must be taken into account. In addition to a technical analysis (conducted for example through parametric costing methods), other considerations include knowing how many member states will contribute, labor costs, revenues generated through commercialization and private investment. This study undertook a preliminary cost overview focusing on three major areas:

- Preliminary technical cost analysis of known system (predicted range)
- Funding input from potential member countries
- Funding input from the private sector

### 7.1.2 International Cooperation

In order to determine levels of international cooperation, the space and exploration budgets for potential nations were analyzed to derive an estimate for funding participation. Though not an exhaustive list, the criteria for participating countries included having a significant space/aerospace budget and having expressed interest in pursuing space and lunar activities. While it is difficult to ascertain the exact amount of contributions per country to a large scale lunar program without doing thorough surveys and primary research, a general assumption of 20% of contributing countries' space budgets is assumed for this model. The nine nations listed in Table 7.1-1 serve as examples of states that have expressed some interest in space exploration and/or could be potential contributors in the future:

**Table 7.1-1 International Partners Budget**

Country	Space Agency	Civil Space Expenditures (2005 US\$MIL)	Estimated Allocation for Luna Gaia (20%)	Contributions over Luna Gaia Life-Cycle (23 Yrs)
Brazil	Brazilian Space Agency	56	11	258
Canada	Canadian Space Agency	216	43	994
China*	China National Space Administration	120	24	552
European Nations	European Space Agency	2,170	434	9,982
India	Indian Space Research Organization	500	100	2,300
Japan	Japanese Exploration Space Agency	2,257	451	10,382
Russia	Roskosmos (Federal Space Agency)	245	49	1,127
United Kingdom	British National Space Centre	306	61	1,408
United States of America	National Aeronautics and Space Administration	15,758	3,152	72,487
<b>Total/year</b>		<b>21,628</b>	<b>4,326</b>	<b>99,489</b>

\*Actual figures unknown

This simple chart shows that with a baseline assumption of 20% participation from each nation’s space budget, total contributions over the 23 year development and deployment phases amount to nearly \$100 Billion (2005 USD) in international contributions. It must however be noted that one dollar does not produce an equivalent product across these nations. Therefore, care must be taken in interpreting the sum of the contributions. Looking at this result, it still becomes apparent that unless one of the contributors is willing to increase its share, alternative sources of funding will be required. The most likely source for additional funding is the participation of private industry in the venture. This may be the best option in order to achieve the mission goals and see the program develop from concept to finish.

### 7.1.3 Private Investment

Incorporating private industry and commercialization into the overall model will likely be an essential component in realizing the technical, scientific, and Earth application goals set forth in the mission statement. Government agencies have recently shown a proclivity for greater private involvement as is evidenced by NASA’s earmarking of \$600M USD for entrepreneurial options between 2006-2010 alone (NASA, 2005) with promises of more to come in the future. While government incentives are important, greater opportunities for industry must come into play in the future.

In order to accomplish some of these lofty ambitions, we have put forward numerous recommendations and means for incorporating private investors. This includes a discussion of public-private partnerships or PPPs (Section 7.2); the policy enablers that must be put in place to pave the road for greater private participation (Sections 5 and 6); and commercialization opportunities that will offer further incentives for industry involvement (Section 8).

### 7.1.4 Technical Cost Assessment of Luna Gaia

Although determining a detailed cost budget is out of the scope of the project, the team undertook a preliminary budget assessment to provide some context of the costs involved. It is also instructive to remember that numerous variable factors could alter the overall budget outlook. Factors that could influence the budget include: timeline changes, new and emerging technologies, material shortages, political will, and international alliances. All of these items can seriously impact the final budget outcome and must therefore be taken into consideration.



The following are a list of assumptions made when compiling the budget:

- Unless otherwise stated, all figures in this section are in 2005 United States dollars
- The budget baseline used is NASA's Exploration Systems Architecture Study (ESAS) recommended budget from 2006 to 2018 of 83 billion because it is the most detailed budget available for a planned lunar mission (NASA, 2005)
- The projected cost is NOT for the Luna Gaia concept itself, but rather for an ESAS-based lunar settlement mission WITH Luna Gaia as a part of it
- The chosen ESAS figure does not include ISS servicing in an attempt to isolate the lunar mission budget from ISS activities
- The percentage of the budget allocated to Exploratory Mission Systems Directorate (ESMD) peaks at Year 8 when ISS servicing stops
- Exploratory missions planned, budgeted and described in Section 1.2 Concept of Operations are considered to be included in NASA 83 billion USD budget figures
- The development cost of the nuclear reactor is included in the ESAS report figures. See Prometheus Nuclear System Technology (PNST) column in Table 7.1-2 the program was cancelled but provides an idea of projected cost. Cost of fuel cells, photovoltaic cells and flywheels are also assumed to be included in the cost
- For budgetary purposes, generic years after program kickoff are used as a timeline instead of calendar years to accommodate funding delays. It is important to note that while the first phase can start at any point, the second phase must be coordinated to begin with a solar minimum.

#### Total Cost Budget

The budget below is divided into two phases. The first phase details the development costs including R&D and procurement of all systems including the habitat. This phase has been calculated for completion by Year 13. The second phase details the deployment and operations costs including transportation, crew costs, and re-supply. This has been phased through Year 23 (10 year span from Year 13). Refer to Section 2.4 for a detailed explanation of program launch schedule and associated costs including launch vehicles:

- The estimated total development costs are \$107.43 billion over 13 years. This represents an increase of 23.43 billion over the ESAS projected development cost estimate of 83 billion (which does not include ISS servicing).
- The total estimated deployment costs over a 10-year period were calculated at \$12.5 billion.
- The total costs for the lunar settlement mission with the Luna Gaia habitat were calculated at \$120 billion over a 23-year development and deployment phase

#### Development Phase

A detailed breakdown by mission was derived from the ESAS development budget chart in Figure 7.1-1. The area was broken down in smaller sections to obtain percentages of total budget used yearly for each mission. These totals can be referenced in Table 7.1-2. Note that the total budget amounts to the 83 billion (USD, 2005) figure discussed earlier.

The projected lunar settlement mission cost breakdown with Luna Gaia is presented in Table 7.1-3. Note that scaling factors were applied to the missions associated with the development of the habitat. For example, a factor of 2 was

used for the *Lunar Surface Systems* because the Luna Gaia concept relies heavily on advancements in robotics to become reality. A factor of 1.5 was used on the *Lunar Outpost* costs to account for the difficulties in closing the loop. Finally, factors of 1.25 and 1.1 were applied respectively to *Lunar Sorties* and *Program Management* to account for the increase in complexity of the project. The total cost of the 13-year development phase with the Luna Gaia concept is estimated at 107.43 billion USD.

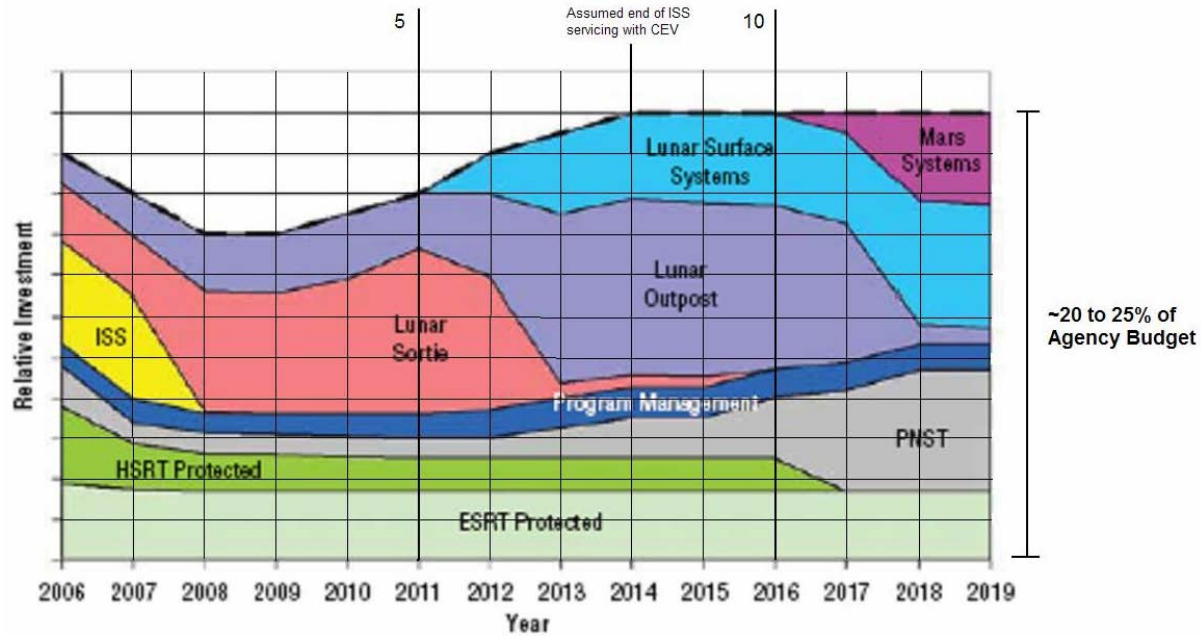


Figure 7.1-1 NASA’s ESAS Overall Research and Technology Budget Broken Down by Mission

Table 7.1-2 ESAS Detailed Estimated Budget Extrapolated from Figure 7.1-1

NASA ESAS Estimated Development Cost (Without Luna Gaia), in billions (USD, 2005)										
	Lunar Sorties	Lunar Outpost	Lunar Surface Systems	Program management	PNST	HSRT (Protected)	ESRT (Protected)	ISS	Mars Systems	Total
Year 1	0.82	0.59	0.00	0.33	0.49	0.85	1.25	1.47	0.00	5.80
Year 2	1.38	0.82	0.00	0.33	0.26	0.59	1.18	0.82	0.00	5.37
Year 3	1.97	0.85	0.00	0.33	0.26	0.59	1.18	0.00	0.00	5.18
Year 4	2.03	0.98	0.00	0.39	0.26	0.59	1.18	0.00	0.00	5.44
Year 5	2.36	0.98	0.00	0.39	0.26	0.59	1.18	0.00	0.00	5.77
Year 6	2.16	1.15	0.33	0.46	0.26	0.59	1.18	0.00	0.00	6.13
Year 7	1.05	2.13	0.98	0.46	0.33	0.59	1.18	0.00	0.00	6.72
Year 8	0.16	2.69	1.38	0.46	0.49	0.59	1.18	0.00	0.00	6.95
Year 9	0.13	2.69	1.38	0.46	0.66	0.59	1.18	0.00	0.00	7.08
Year 10	0.07	2.69	1.64	0.46	0.82	0.33	1.18	0.00	0.00	7.18
Year 11	0.00	2.46	1.64	0.46	1.18	0.00	1.18	0.00	0.16	7.08
Year 12	0.00	1.15	1.80	0.46	1.70	0.00	1.18	0.00	0.82	7.11
Year 13	0.00	0.33	1.97	0.46	1.97	0.00	1.18	0.00	1.31	7.21
<b>Total</b>	<b>12.12</b>	<b>19.50</b>	<b>11.11</b>	<b>5.44</b>	<b>8.95</b>	<b>5.90</b>	<b>15.40</b>	<b>2.29</b>	<b>2.29</b>	<b>83.00</b>
<b>% of Budget</b>	<b>15%</b>	<b>23%</b>	<b>13%</b>	<b>7%</b>	<b>11%</b>	<b>7%</b>	<b>19%</b>	<b>3%</b>	<b>3%</b>	<b>100%</b>

**Table 7.1-3 Luna Gaia Projected Cost Derived from ESAS Estimated Budget**

Projected Cost With Luna Gaia in billions (USD, 2005)										
Program Total Cost	12.12	19.50	11.11	5.44	8.95	5.90	15.40	2.29	2.29	83.00
Factor	1.25	1.5	2	1.1	1	1	1	1	1	
Luna Gaia Adjusted	15.15	29.24	22.22	5.98	8.95	5.90	15.40	2.29	2.29	107.43
% of Budget	14%	27%	21%	6%	8%	5%	14%	2%	2%	100%

### Deployment Phase

The deployment costs associated with the Lunar Settlement mission with Luna Gaia is primarily driven from the launch schedule and selected launch vehicles and re-supply missions as presented in Section 2.4 (cost shown in Table 7.1-4). The other factor considered in the estimate is the cost of having crew at the outpost. This cost was estimated to be 1 million USD a year per crewmember based on data from the ISS (Wertz, Spring 2005). Finally, a factor of 1.2 was applied to the total to obtain a value similar to what NASA calls "Full Cost" (NASA, 2005) to account for the maintenance of contractors and support infrastructures for the duration of the mission. The resulting cost for this phase is 12.54 billion.

**Table 7.1-4 Deployment Cost for Lunar Settlement Mission with Luna**

Deployment Cost in billions (2005 US\$)												
	Phase	ARES I # of Launches	ARES I Cost	ARES V # of Launches	ARES V Cost	Re-supply # of Launches	Re-supply Cost	Manpower cost/person	# Crew	Cost	Total	Full Cost (20% Factor)
Year 14	C1	2	0.126	2	0.876	0	0	0.001	4	0.004	1.01	1.21
Year 15	C1	2	0.126	2	0.876	0	0	0.001	4	0.004	1.01	1.21
Year 16	C1	2	0.126	2	0.876	0	0	0.001	6	0.006	1.01	1.21
Year 17	C1	2	0.126	2	0.876	0	0	0.001	6	0.006	1.01	1.21
Year 18	C1	2	0.126	2	0.876	0	0	0.001	6	0.006	1.01	1.21
Year 19	C1	2	0.126	2	0.876	0	0	0.001	6	0.006	1.01	1.21
Year 20	C1	2	0.126	2	0.876	0	0	0.001	6	0.006	1.01	1.21
Year 21	C2	2	0.126	2	0.876	2	0.12	0.001	10	0.01	1.13	1.36
Year 22	C2	2	0.126	2	0.876	2	0.12	0.001	12	0.012	1.13	1.36
Year 23	C3	2	0.126	2	0.876	2	0.12	0.001	12	0.012	1.13	1.36
<b>Total</b>		<b>20</b>	<b>1.26</b>	<b>20</b>	<b>8.76</b>	<b>6</b>	<b>0.36</b>			<b>0.072</b>	<b>10.45</b>	<b>12.54</b>

### Gaia

## 7.2 Public-Private Partnership Options

In 2004, US President Bush called for a new Vision for Space Exploration that laid out a blueprint for returning to the Moon, Mars, and beyond. The vision outlines ambitious goals for technological development and human achievement promising to usher in a new era in human space flight, exploration, and settlement. While the plan allows for international cooperation and burden-sharing, the details pertaining to the international partnership remain relatively undefined. It is our contention that without a carefully constructed model enabling both private and public participation, the goals and directives of the Vision and therefore, Luna Gaia, will likely never come to fruition. Thus this project assesses two possible models that nurture a close public-private partnership within each participating nation as well as the international cooperative at-large. The two models analyzed for Luna Gaia include a:

- 1. Government/Public-led PPP model
- 2. Private-led PPP Model

### 7.2.1 Partnering for Success

The Luna Gaia endeavor will be a massive undertaking requiring backing from numerous nations for its goals to be realized. In order to find the support for

sustainable funding, government and private options must be considered. At this stage in time, it is unrealistic to believe that private corporations will be incentivized enough to go it alone nor would it be prudent to allow them to do so. In fact; the current plan, as delineated by the mission design team, calls for the use of the Crew Exploration Vehicle (CEV) for human and cargo transport as well as Ares I and V vehicles, therefore necessitating some public involvement.

However the question remains how much private investment is warranted, possible, and necessary for governments to see the project to the end? Also, what is the preferred path to enable greater efficiency, achievement of mission goals, and profitability? It is therefore instructive to assess the public/government role in the development of Luna Gaia as well as the short- and longer-term benefits that can be derived from private funding. After a brief discussion of the role of each, the two models for Luna Gaia will be put forward.

### **7.2.2 Government Participation**

Government participation plays a critical role in any public-private partnership chiefly by reducing risk for the private sector. These roles include developing the necessary policies, legal framework, technological development as well as financial incentives for potential private investors. Without these elements incorporated within the partnership structure, investors will have a difficult time forecasting a return on investment and justifying participation.

In order to pave a path forward for industry involvement, governments will likely be called upon to provide significant assistance with (Sadeh and al., 2005):

- **Research & Development.** Government R&D support is necessary to provide early phase development, test and evaluation of products as well as the infrastructure to carry out these processes. Industry is less-inclined to undertake major precursor and R&D initiatives for unproven technologies due to the high cost and non-guarantee of appropriation.
- **Procurement and Purchasing of Commercial Services.** In either a government-led initiative or a true PPP, governments can benefit from purchases of commercial services and by contracting out major portions of the mission. In general and particularly in the case of the United States today, it is relatively rare for government agencies to develop everything in-house. Cost savings and economies of scale are to be had by purchasing commercial-off-the-shelf systems (COTS) where possible as well as allow industry players to compete by issuing request for proposals (RFPs). This also benefits industry by driving growth and through the creation of enabling technologies. Examples of this include contracts from NASA, the Department of Defense, and the General Services Administration (GSA) (Sadeh and al., 2005).
- **Technology and Knowledge Transfer.** Government entities would play a role in the transfer of technology out of the R&D phase to commercial entities as well as the know-how for implementation.
- **Intellectual Property Rights and Patent Protection.** A critical government function to allow industry involvement on Luna Gaia is the creation of property rights for activities conducted on the Moon. For example, if a private corporation is called upon to mine the Moon for hydrogen or collect samples of Moon rock, that company will want assurances that it has some intellectual property rights. Without it, no stable business model exists for the contractor who is typically beholden to debtors, creditors, and other financiers. For a more detailed analysis refer to the Policy and Law Sections (Section 5 Policy Issues and Section 6 Legal Issues).

- **Financial Incentives.** Governments may also assist in providing financial incentives to attract private investors and developers (Peeters, 2001). This may come in the form of low-interest loans, tax benefits and credits, as well as subsidies. Corporations would receive these incentives in return for developing a certain module of the lunar base for example; government players would then lease out the facility for its mission requirements.
- **Innovative Measures.** The government may also spur competition and create an optimal environment for industry through the promotion of prizes and other contractual awards. Prizes for lunar robots or innovative gadgets to make the habitat on the Moon more convenient may be productive and create new investment opportunities. Allowing corporations the ability to retain the rights to their design for use on Earth may provide another incentive for private involvement.

### **7.2.3 Private Participation**

The private sector is mainly concerned with developing a business model that will generate profits and a high return on investment. Without legal precedents and government assurances no private-public model is feasible for the lunar construct. For successful financing of Luna Gaia, it is imperative that a significant stake of the project is carved out for the private sector.

Private sector involvement is critical to the long-term success because government investments may not be sufficient, efficient, nor stable. It supplements government funding to provide faster, cheaper and more effective technologies and is key to any sustainability because of the jobs created. This network and growth of the industrial base helps establish a base for public - and therefore - political support. Changes in direction and cancellation of projects would be much more difficult to come by regardless of the political environment, thereby creating broader security and sustainability for the project.

Thus some critical advantages of incorporating private investment and support include innovative technologies, efficiency, lower costs, greater accountability (in timeline and schedule), transparency of activity, and the basis for broader political support.

#### *PPP Models*

This section will assess two recommended models for pursuing public-private partnership options to enable the necessary funding framework. The models presented are of a public-led PPP initiative versus a private-led PPP. While both models have their disadvantages, each has significant advantages that already vastly improve upon a go-it-alone model for either government or industry. At the heart of the PPP concept is optimum risk allocation. Thus in both models, risk mitigation and capital formation programs will need to be enabled by government and industry respectively for a successful synergy of the PPP (Peeters, 2001).

#### *Model 1: Public-Led PPP*

Enabling the mission plan and forging a sustainable funding stream for a lunar base concept will require a carefully constructed model that takes into account the necessary political, economic, and risk factors engendered by such an undertaking. The first model relies on large public/government involvement to enable and essentially manage the overall construct, Figure 7.2-1. The government's chief role will be to manage and oversee the private partnership through the purchasing and procurement of commercial services, providing the necessary financial incentives

and creating a regime for intellectual property rights that will enable industry to maintain the rights to their design for other Earth applications. This model calls for the eventual phase-in of increased industry control and input. For example, industry would be allowed to commercialize some of its modules down the road.

### Public-Led PPP

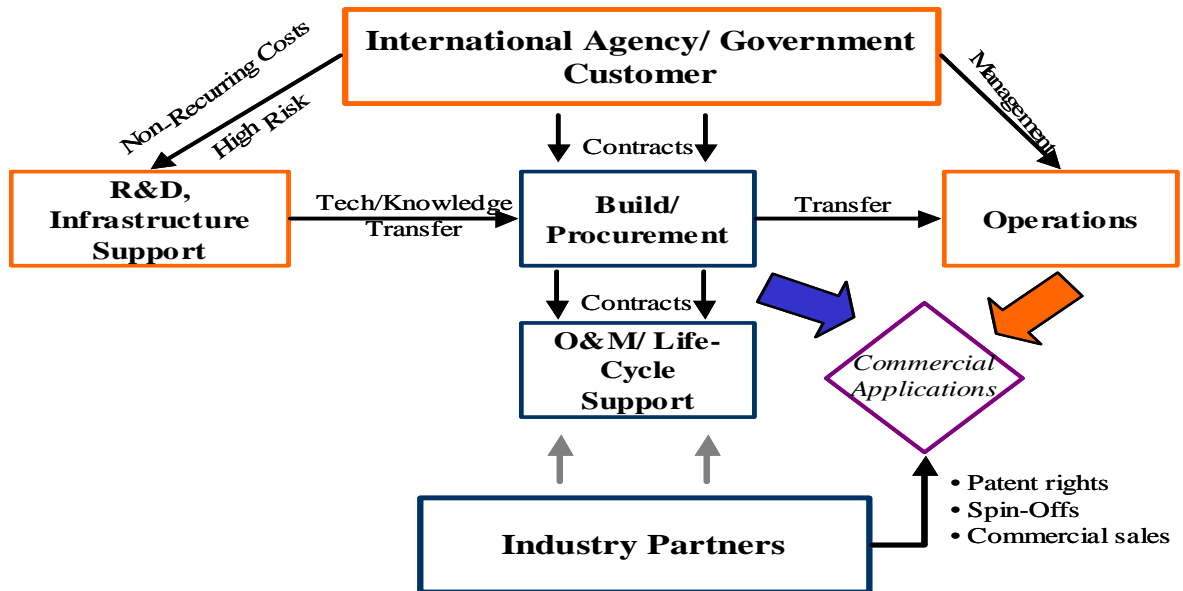


Figure 7.2-1 Public-led PPP Diagram

### *Model 2: Private-Led PPP*

The private-led PPP model would essentially establish a corporate entity that owns and manages the mission design and architecture, Figure 7.2-2. Such a corporation acts as the systems manager for design and construction, and contracting with private firms to undertake the work. This would in turn be subsidized by governments to help provide the necessary environment for risk optimization.

The model would drive a more “marketplace” approach to the Moon by treating its resources as private goods (Sadeh and al., 2005). Thus access would be based on some sort of property rights regime (see Section 5.3.1, Property Rights) and businesses would be largely driven by supply and demand. In the case of Luna Gaia, there would be high demand from the governments involved as the first and core customers. However, there would not be any limitations as to whom they could sell to or the types of commercialization plans to undertake. As the core customers, government parties would be able to drive specific developments and missions for the lunar base; however, they would not have total control over its direction. Thus if a private-led PPP is established, careful policy and legal considerations will have to be mapped out in order to ensure reciprocity and agreement between the private and public entities. An example of this is the Communications Satellite Corporation (COMSAT) which was established by the US Communications Satellite Act of 1962 and allowed for a “federal corporation to administer satellite communications for the US” (Sadeh and al., 2005).

**Private-Led PPP**

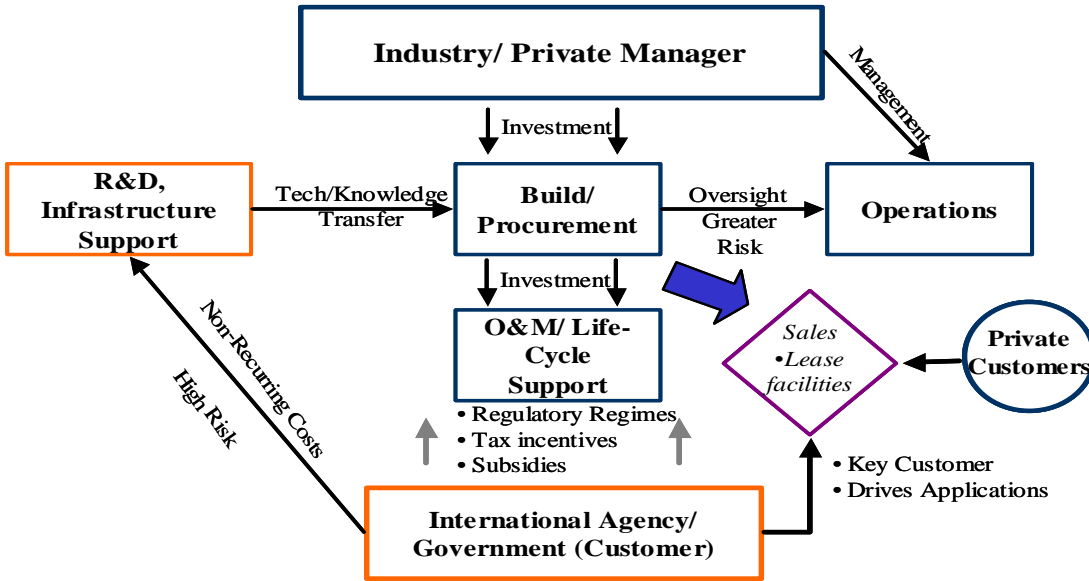


Figure 7.2-2 Private-led PPP Diagram

*Recommendations*

Both models described are merely representative of the types of partnerships available between industry and the public sector. Each model rests on certain assumptions since the PPP relationship is only feasible when both parties deliver what is promised. While the private-led model offers some ideal efficiency and timeline advantages, the public-led model is likely the more prudent one to adopt. This assessment hinges on one important unknown: the (private) market demand for lunar facilities and development. Without careful trade studies and market analysis, it will be difficult to convince investors that there are greater Earth and commercial applications beyond government use and that these applications are feasible within a short timeframe. Investors will be looking for a short- to mid-term turnaround on investment and could become wary of a high-risk venture such as development of the Moon without assurances of a long-term government commitment. The advantages and disadvantages of each model are described below:

	Advantages	Disadvantages
Public-Led	<ul style="list-style-type: none"> <li>• International Coalition to share costs</li> <li>• Develops R&amp;D: Highly Accountable</li> <li>• Not motivated solely by profits</li> <li>• Covers substantial portion of risks for private industry</li> <li>• Guaranteed source of funding</li> <li>• Development of industrial base</li> </ul>	<ul style="list-style-type: none"> <li>• Private investment dictated by what government sector allows</li> <li>• Some efficiency gains lost (bureaucracy)</li> <li>• Procurement and implementation phase generally slower</li> </ul>
Private-Led	<ul style="list-style-type: none"> <li>• Incentive to get infrastructure built quickly</li> <li>• Private capital to balance public deficits</li> <li>• Better financial management (stakeholder driven)</li> <li>• Competition leads to innovation, cost reduction</li> </ul>	<ul style="list-style-type: none"> <li>• Could create ill-informed decision-making to drive profits</li> <li>• Public sector jobs/employment rights threatened (political)</li> <li>• May not follow best interests of the public</li> <li>• Nothing is guaranteed: greater risk for private corporations</li> </ul>

## 7.3 Risk Management/Insurance, Indemnifications, Liability

### *Current situation*

Traditional insurance coverage for space activities can be divided into three main groups:

1. Physical loss or damage,
  - a) on pre-launch phase/construction,
  - b) during launch and commissioning,
  - c) during operation;
2. Third party liability,
3. Consequential loss, warranties.

The problem in this relatively young industry is that there have been few precedents, making the cost of insurance very volatile. Currently the premium rates amount to about 0.35% to 1.75% of the insured value on pre-launch phase, 15-20% on commissioning phase, 1.5% to 3.5% per annum during operation and 0.15% for launch liabilities (Elson, 2006). This will need to be addressed to make Luna Gaia attractive to businesses.

The launching state is internationally liable for damage caused to another state or to its natural or legal persons by a space object or its component parts on the Earth, in air or in outer space. Liability is unlimited in amount (Article VI Outer Space Treaty). By ISS IGA all partner states and their related entities agree to a cross waiver of liability; as a result the liability of a participant in a space project towards other parties will depend on whether this party is a related entity or a third party:

- If it is a related entity, the cross waiver of liability means that no indemnification is claimable for any damage from another related entity. As a result, participants in ISS for example, do not have to have insurance against risk of damage they cause to others, they can take insurance for their own damage, or their own astronauts.
- If it is a third party, states concerned require the launching authority to take insurance to cover the damage suffered by third parties from pre-launch, launch or operation activities. The minimum value of insurance will vary from one country to another. This insurance coverage is available only on specialized insurance markets usually from 100 to 500 million dollars. In excess of insurance coverage the amount claimed will be compensated by the state.

### *Astronaut Coverage*

The coverage of astronauts themselves can be divided into two groups:

- bodily injury or death of an astronaut,
- damage or bodily injury caused by astronauts.

Bodily injury or death of astronauts is covered by insurance policies usually starting from the astronaut's entering the vessel and ending after return to Earth or mission abort in case of failure.

Damage or bodily injuries caused by astronauts to third parties are regulated as per requirements of the liability convention (de Dinechin, 1998). The cost of the third party liability insurance will vary a lot from country to country depending on license requirements of a particular launching state. Pre-launch and launch third



party liability insurance is very important and is more expensive than operation third party liability insurance as the risk of causing and moreover of being proved to have caused the damage to a third party in space is very small.

The main insurance policy features will include: insured parties (launching governmental or private agencies, manufacturers or organizations rendering services etc), policy period (the expiration date of the insurance policy), limit of liability (cost and expenses), insuring agreement and exclusions.

## **7.4 Commercialization**

Getting into space and making it viable is almost a technology in itself. The development of space technology incorporates the entire spectrum of technologies to date, from propulsion to computing. Space business also provides a development-oriented feedback loop. As we confront new challenges in space we will develop new solutions, systems and technologies. These will serve to make space more efficient and accessible, and can in turn be used in traditional business areas back on Earth.

### **7.4.1 Private Sector Efficiency**

Rather than assuming sole logistic and financial responsibility for the development and operation of the lunar base, the governing agencies should consider involving companies directly in the development of the base. This can take the form of RFPs and building contracts.

Once built, current space agency functions could be contracted or licensed to private companies. There are commercial enterprises currently developing human spaceflight capability. This capability is projected to include moon missions in the near future. The greater cost efficiency in the private sector can be harnessed by contracted out Earth-Moon transportation development, scheduling and flying once the agencies have provided the initial vehicle development and funding. Equally, day to day lunar base operations can be streamlined by being run by private for-profit companies.

### **7.4.2 Private Interests on the Moon**

A Moon base, or the regular, predictable transportation to the Moon has many other potential commercial uses. Some of these options are listed here briefly, while one of them are explained in greater detail as case studies.

*Permanent human knowledge reservoir:* a potential market of individuals, religious or other interest groups may form a potential market for storing information in a permanent reservoir on the Moon.

*Moon Mining:* the potential exists for producing rocket fuel from the abundant hydrogen and oxygen on the Moon and for extracting other valuable substances (Thorpe, 2003).

*Tourism on the Moon:* the possibility of operating a casino on the Moon is a topic of current discussion between a private aerospace company and NASA. The Moon as a tourist destination can be discussed later in the development of Luna Gaia, once the base has been established and the technology proven. For a discussion on whether space tourists can be considered astronauts, please see Chapter 5, Policy.

*Moon burials:* Celestine, an American company, currently offers a service called “Memorial Spaceflights” that allows a customer to send between 1 and 7 grams of

cremated human remains into Earth orbit, into deep space, or onto the surface of the Moon. Celestine charges between \$12,500 and \$67,495, depending on the weight flown (Celestis).

*Entertainment / Filming:* Those who have ridden the Concorde or climbed mountains are rarely asked about the cost to benefit ratio – they are asked about the experience. The experience is what will fuel interest in Luna Gaia and eventually space tourism. People will pay to go to the Moon initially because it has not been done before, by other than elite, trained astronauts. Then, they will continue to go there because they've been everywhere else, and because everyone on planet Earth knows the Moon. Right now it is the only place we can all see but cannot visit. The lunar habitat can change that, by tapping into humanity's urge to visit the Moon.

The Artemis Project is a for-profit venture created to capitalize on the entertainment value of building a Moon base. The building of the Moon base would comprise entertainment, before, during, and after construction. Funds from other entertainment projects are to provide initial capital investment, and then the base itself would generate revenues from being entertainment.

By comparison with similar mass-marketing ventures that link movies and TV shows with associated merchandise, the Project estimates that it could generate five billion dollars just from the first flight (Berinstein, 2002). The business plan includes tying in different associated markets, including motion pictures, videotapes, toys, video games, scientific data, magazines, books, games, and product endorsements. Marketing tie-ins such as base models and T-shirts is estimated to be a market of minimum 1 billion USD annually (Peeters, 2000).

It is expected that the astronauts in this venture would tap into their celebrity and high-profile status and endorse products as do professional athletes on Earth. Additionally, product placement will be used as a profit generator, with logos being displayed on astronaut clothing. This idea has a precedent: Pizza Hut paid the Russians to display its logo on the fuselage of the proton rocket that delivered the Service Module of the ISS to orbit in 2000, and astronauts filmed a RadioShack advertisement onboard.

We recommend that developers consider adopting some of these ideas to help finance Luna Gaia. Delivering the development of the lunar base to the general public as a form of entertainment has the potential to capture public imagination and interest.

*Corporate Sponsorship* Corporate sponsoring can be a potential source of income for the base (Peeters, 2000). High tech companies could be willing to sponsor base modules or transports, in an analogous manner to Olympic Games or other sporting event sponsors.

*Moon on Earth:* Having ordinary citizens visit the lunar base is not a prospect within the immediate project scope. However, many people may be willing to pay for an opportunity to visit Earth mockups of Luna Gaia.

There is a proposed Moon casino and resort in Las Vegas, designed to give people the feeling of what it's like to be on the Moon (David, 2002, Resorts). Running a facility of this type is not only a commercial opportunity, but an opportunity to connect with the public in a hands-on way as part of Luna Gaia's public relations program.

## 7.5 Public Relations

Public relations plays a critical role in the success of a space program. In many cases, it does not just influence public opinion but creates it, defines and maintains the identity of the whole project. Public opinion itself is very important for Luna Gaia as one of its aims is to benefit and contribute to mankind. The public's approval of space activities has been relatively steady since the days of Apollo yet it has experienced its highest drops in times of catastrophic failures and loss of life. A recent Gallup poll (The Gallup Organization, 2005) show that in the US more than  $\frac{3}{4}$  of the public supports NASA's new plan for space exploration, which is in sharp contrast to the 45% approval seen in 2002 (David, 2000). In the context of Luna Gaia's objectives to achieve a close loop system, the project will inevitably be associated with the previous attempts to create closed loop habitats on the Earth, where some problems were admitted too late or not at all. The project will therefore benefit from distancing itself from those highly publicized failed attempts and educate the public on what is being done, with a focus on solutions to previous fatal flaws.

In the days of the space race at the height of the Cold War, the US space program enjoyed tremendous support as it had a clear vision and a goal in mind. Since those days, the program has been plagued by what lawmakers call a "lack of guiding vision". The Report of Columbia Accident Investigative Board (CAIB) outlines in its recommendations that "(...)future space efforts must include a human presence in Earth orbit, and eventually beyond" and that no such vision appeared imminent (NASA, 2003a). Attracting public and media attention to this project will not be a difficult task with the clear goals and vision of President's Bush plan of 2004 finally addressing this pressing need (Smith, 2004). The program will get plenty of free print space and broadcast time because media representatives will consider the information pertinent and newsworthy for their audience (Shimp). Maintaining interest in the program with innovative methods, along with respect of the schedule, are crucial to maintaining support and to reduce the possibility of losing funding.

We worked out some key recommendations for a multi-faceted approach aimed at winning the support of both the public and mass media:

- 1) General education information on the project placed in mass media, with a focus on achievements, milestones, progress and potential benefits to science and the public. The main aim here is to create the desirable public opinion and to win public and media's support;
- 2) Provide society with a wide range of the latest and the most accurate information on the project. The main aim here is to keep its support and attention at the same level which can be achieved through different PR, advertising and communication instruments:
  - Holding various seminars and events to attract more public attention to the project,
  - First-hand information (Tele-communication conferences with the crew),
  - Constantly updated web-site with latest news and free e-mail news subscription, weekly "Status Report", may be even including a "virtual tour" to Luna Gaia.
  - Webcam/web hosting with a partner or sponsor. It may be a tool to attract some private investors, partners or sponsors while offering a portal for public outreach.
  - Field diaries of astronauts on the base, showing the human side of living in a Moon habitat.
  - Joining organizer's groups of "cafe scientifique" which is a forum for discussion of interesting and very important scientific topics and issues,

open for everyone, even for people not involved in science, but who has a strong interest in it.

- Media partners for in depth coverage, interviews can also be a very successful tool. One of the ways to win the public and media's support after sending astronauts to the Moon base can be sending a journalist or a reporter to the Moon base to highlight the experience of living in a closed loop habitat for an ordinary person.

3) Two-way communication is also a very important article — the company should be listening as well as talking and the various PR venues often provide immediate feedback.

4) We should also keep in mind that the public often sees public relations messages that have been covered by the media as more neutral or believable so it is very important to win the media's interest and trust by providing the accurate information and service for the multimedia and educators.

All of the above mentioned measures will help not just to create and keep a positive image of the whole Luna Gaia project to society but will also help to attract public's attention to space activities and exploration of space which undeniably have a huge impact on all mankind.

---

# Earth Applications

## 8.1 Importance of Earth Applications

The identification of potential Earth applications to promote sustainability on Earth has been a primary consideration throughout our research and design efforts. As the financial investment required to build a lunar habitat is important, assessing the possibility to develop new knowledge and technologies will be a major component of any government's or corporation's cost/benefit analysis. The accelerated development of beneficial applications also answers the public's constant questioning of the usefulness of space exploration. Therefore, an effective demonstration of both the short and long-term Earth applications will be a crucial first step in raising the necessary political, financial and public support for a lunar habitat.

By definition, the design of a closed loop lunar habitat will necessitate the development of innovative technologies, innovative uses of existing technologies, and innovative operational strategies and knowledge. Technologies and strategies developed to optimize food production, waste management, water recycling and filtration, air quality control, and contamination prevention and treatment are only a few examples of potential applications that could contribute significantly to the sustainable development of Earth. Improvements to water filtration technology alone, considering that 1.3 billion people do not have access to clean water (Mukai, 2006), could provide enormous benefits to people on Earth.

Climate change, peak oil, air pollution and the declining quality and quantity of clean water resources are significant issues on both local and global levels which compromise the sustainability of human life on Earth. Governments around the world are dedicating enormous amounts of economic and intellectual capital to the development of effective resource management, environmental monitoring strategies and related sustainable technologies. To this end, the expertise, experience and enabling technologies produced by the construction of a closed loop lunar habitat could contribute significantly to these critical fields of knowledge.

The opportunities to benefit from these new technologies on Earth are numerous. A more detailed case study of bioprocessing is presented in the next paragraphs, followed by several promising examples in a variety of fields.

## 8.2 A Case Study in Bioprocessing: The Membrane Bioreactor

A bioprocessing technology using a cyanobacterium called *Spirulina* will play a primary role in the lunar habitat's air regeneration process. In this section, a detailed explanation of this technology and its potential application on Earth will be provided.

It is generally appreciated that the rate of photosynthesis (oxygen production) and biomass production of microalgae significantly exceeds that of higher plants. A vertically stacked membrane bioreactor, coupled with a solar tracker and photon delivery system, can act as a lightweight oxygen production (and carbon dioxide recycling) system with minimal water requirements. This system was first developed for the US Department of Energy for carbon sequestration. Water is fed via capillary action through the weave of the membranes, keeping the algal cells “wet” and delivering appropriate nutrients. Coupling full-spectrum, solar tracking photon collection with fiber optic delivery allows the bioreactor to optimize growth and further reduce system footprint. Moreover, coupling the delivery of water (during normal growth phase) and harvesting systems into the same fluid delivery mechanism has improved growth rates, while reducing system costs.

Preliminary estimates suggest that a membrane bioreactor of 80 m<sup>2</sup> having twenty 2m X 2m membranes, each spaced 10 cm apart, would need 8 m<sup>3</sup> of volume and a total of 70 L of water to produce a daily oxygen supply for a 15-member crew. Also, 2.7 kg of dried microalgal biomass would cover energy requirements for the same crew if obtained microalgal biomass is well balanced with essential vital components like amino acids, etc.) (Bayless et al., 2006).

### **8.2.1 Photon Collection and Delivery**

In order to utilize solar photons at maximum efficiency, the light delivery subsystem must deliver a sufficient quantity and quality of photosynthetic photons to deep within the bioreactor and minimize light loss due to reflection and absorption. Direct, filtered sunlight is collected and delivered into the bioreactor via collection optics and large core optical fibers. The visible light from the sun reflected from the collector dish and secondary optics is launched into an array of optical fibers. These large core fiber optic cables then supply photons necessary to support photosynthesis, using special distributors located between the vertical growth membranes.

By controlling attenuation through the fiber optic cables and using specially designed distributor plates made from similar materials, a uniform distribution of photons may be supplied, typically at a rate between 100-200  $\mu\text{mol}/\text{m}^2\text{s}$ . This distribution is a key element in the reactor design. The sunlight, originally collected by tracking mirrors (optimizing solar collection) will provide suitable photons at a rate over 2000  $\mu\text{mol}/\text{m}^2\text{s}$  of throughout the day. However, at this rate, most photons would be wasted, as photosynthesis in thermophiles occurs at much lower light levels of 100-200  $\mu\text{mol}/\text{m}^2\text{s}$  (Bayless et al., 2006).

Filters removing unwanted portions of the solar spectrum (IR, some UV) allow them to be used for photovoltaic production of electricity needed to power the auxiliary components of the system.

### **8.2.2 Growth Media Transport System**

The growth media transport system consists of two distinct parts – a circulating fluid system and liquid distribution system. The circulating fluid system is powered by a closed loop pump, a gravity-driven transmission system where water containing defined levels of nutrients and soluble carbon (or void of soluble carbon) is delivered to the membrane support for the organisms. The water then flows through distribution headers of the liquid distribution system and into the fibers by gravity-assisted capillary action.

### **8.2.3 Organism Harvesting and Repopulation**

The harvesting system provides a way to remove mature organisms or reduce cell density to promote further cell division and re-populate the membranes with developing organisms, thus maximizing carbon uptake. Preliminary tests indicate that microalgae, removed in "clumps" from the growth strata, are easily agitated into a diffused state. Mature microalgae (organisms with a low potential for carbon utilization) can be removed and microalgae that are maturing (organisms with a high potential for carbon utilization), can be re-populated on the growth strata.

Harvesting from the experimental bioreactor is done using the water distribution system to minimize the need for additional components. By increasing the water pressure to the distribution header, a great flow of water per unit area of membrane is achieved, creating a gentle washing effect. This gentle washing is critical, so as not to shock the organisms and delay continued growth. Furthermore, the gentle washing process is generally 30-50% effective (on a mass basis) in removing organisms from the membrane substrate, which is needed to maintain cell density to sustain continued cell division.

### **8.2.4 Improving Air Quality on Earth**

Today's increasing levels of carbon dioxide and other greenhouse gases are a consequence of a number of factors, including deforestation trends and a global economy built on fossil fuels such as coal, gas, and oil. When greenhouse gases trap solar energy within the atmosphere, the temperature of the Earth's surface increases and there is a resulting change in global weather patterns. Air pollution resulting from industry and congested roadways is particularly acute in urban areas, where the health of dense populations is compromised daily.

Within the popular media, climate change is strongly debated, yet within the scientific community it is supported by overwhelming and undeniable evidence. As the continued health of humans is dependent upon the continued quality of air on the planet, the importance of air quality monitoring and control will only increase with the current heating and pollution trends. For this very reason, the application of bioprocessing technology to convert carbon dioxide to oxygen on Earth could play a crucial role in increasing air quality and maintaining the sustainability of urban areas on Earth.

A unique feature of this proposed 'multilayered microalgae wall' is that there would be no need for direct sunlight as there was for the Bio-Lung. An optical fiber network would deliver the required quantity and quality of photosynthetic photons to the bioreactor.

## **8.3 Other Potential Applications**

### **8.3.1 Food Production**

By developing optimal growth and nutrient regimes for Luna Gaia's closed loop agriculture system, many opportunities for knowledge and technology transfer to food production on Earth will result. Knowledge of plant growth and photosynthesis requirements gained in space can be applied to controlled-environment agriculture on Earth, such as that in greenhouses, the cut-flower industry, and hydroponics. Moreover, the research can be used for the researchers studying the use of plants to control the environment in office buildings. Knowledge gained from the development of growth media and water delivery systems for plants on the lunar surface might be useful in further development of subirrigation systems, as well as water-conservation techniques for arid and semi-

arid agriculture conditions. One such technique developed for water-conservation involves directing water underground where roots need it most, rather than spraying water on top of the ground, where much of the water evaporates before crops can use it.

Ideal plant species for food production at Luna Gaia would have short stalks to save space, few inedible parts, grow well in low light, and be resistant to microbial disease. Crops which have these characteristics could contribute to food production strategies on Earth, especially in areas with low quality soil. Development of methods for soil restoration

Soil restoration is another area rich in potential Earth applications. On the lunar surface, soil nutrients can be restored as result of more intimate nitrogenation through controlled cycles. The research and development performed in soil restoration may serve to enable more intensive crop production on Earth.

### **8.3.2 Contamination Technologies and Prevention**

Important advances in contamination prevention technologies will need to be accomplished if a lunar laboratory is to be realized. Such technological advances could contribute significantly to our ability to monitor and control pandemics and diseases on Earth, which will invariably become more pressing in the next decade. Improved technologies developed for Luna Gaia could also make significant contributions to sterilization techniques, decontamination measures, encapsulation of specimen to only name a few.

### **8.3.3 Water Filtration**

Access to clean drinking water is and will continue to be a critical issue for the sustainability of human life. Water filtration methods utilizing higher plants and microalgae optimized for Luna Gaia may offer innovative methods of improving water quality on Earth and may be particularly applicable to rural communities. For a more detailed description of the water filtration process used for Gaia please see Section 3.2.8, Recommended Solution LuGuLiSuS.

### **8.3.4 Mining Techniques and Technologies**

Production of metals as a byproduct of lunar and Martian oxygen generation may, once the technology has been proven to be safe, be a commercial means to harvest metals on Earth from ores, or a means for doing so on asteroids.

### **8.3.5 Power Generation**

In light of Earth's declining fossil fuel resources, advancements in solar thermal and nuclear fission technology developed for Luna Gaia could provide important contributions to renewable energy generation on Earth. For solar thermal, materials advances will need to be made in polymer reflective membrane technology to improve the specular reflectance of materials and to improve the resistance of the surface coatings to dust contamination. In regards to nuclear fission, technological advances will need to be made in order to generate a higher amount of power at low reaction temperatures. Significant improvements will also be needed to make the transportation, deployment and operation of small nuclear reactors safer and easier. Such innovations will make nuclear power a more attractive option to produce power around the world.



### **8.3.6 Testing Innovative Social, Political and Economic Processes**

While the Moon is commonly recognized as a potential testing ground for innovative technologies, the potential it holds for testing innovative political and economic processes is rarely recognized. By virtue of its proximity to and isolation from Earth's high inertia political and economic processes, the Moon may provide a promising testing bed for innovative modes of governance, novel forms of social organization and management structures as well as innovative modes of production and consumption. The potential benefit and application to Earth could be very large but may be difficult to estimate. However, in light of today's pressing political, economic and environmental problems, the benefits and risks of utilizing the Moon to investigate the relative strengths of different economic and political systems merits further analysis (for more details, see Chapter 4 Philosophical and Societal Issues and Chapter 5 Policy Issues).



---

# Conclusion

Throughout our evolution, human innovation has created technologies that have enabled us to adapt to new and hostile environments. Life support technologies for humans in outer space have evolved very little since the dawn of the Space Age and still to this day are mostly based on methods developed in the 1940's to 1960's (Kliss, 2006a). As we venture into a new chapter of human space exploration, we must bridge the technology gap from old physico-chemical systems into new bioregenerative systems. Humankind's leap from its terrestrial cradle into permanent extraterrestrial settlements requires a corresponding leap in supporting technologies, a leap which calls for a critical change in philosophy. Arthur C. Clarke described human space exploration as a "technological mutation", one which developed before its expected time. With the advances in biotechnology in the last few decades, we are now equipped with the tools necessary to effectively close the life support loops. While the tried and tested methods will serve as support systems, establishing a lunar habitat will call for the adoption of newer techniques for expansion into an alien environment and the next stage of human civilization.

This report describes a path for humankind to take this next step in evolution with the Luna Gaia concept. Establishing a permanent human presence in space through continued exploration and settlement of celestial bodies from the Moon to Mars and beyond has excited the imagination of humans for time immemorial. Luna Gaia's innovative approach to architecture and closed loop systems sets the stage to make this dream a reality. Many recommendations were put forth in bringing this concept to life.



## References

- AGENCY, E. S. (2006) *ILEWG International Conference on Exploration and Utilization of the Moon, Lunar Beijing Declaration*. Beijing.
- AGRICULTURE, U. S. D. O. (2005) *Dietary Guidelines for Americans 2005*, U.S. Department of Health and Human Services.
- ALEJANDRA MENCHACA, A. R., SCOTT SHEEHAN (2005) Long Duration Orbiter Environmental Control and Life Support System. *Aircraft Systems Engineering*.
- AMES, N. (March 23, 2006) *Crew Training and Support Systems* Ames Technology Capabilities and Facilities, NASA Ames Center.
- ANANYEV, G. & DISMUKES, C. G. (2005) *How fast can photosystem II split water? Kinetic performance at high and low frequencies*, Princeton, Princeton University.
- ARCHITECTURE, C. O. (2006) Chandigarh College Of Architecture - Preamble, Inception and Brief History. Chandigarh - 160012, India, Chandigarh College Of Architecture.
- BAYLESS, D., BROWN, I., JONES, J. A., KARAKIS, S., KARPOV, L. & MCKAY, D. S. (2006) Novel concept for LSS based on advanced microalgal biotechnologies. *HABITATION 2006 - Conference on Habitation Research and Technology Development*
- BERINSTEIN, P. (2002) *Making Space Happen: Private Space Ventures and the Visionaries Behind Them*, Plexus Publishing.
- BISHOP, S. (2002) Evaluating Teams in Extreme Environments: Deep Caving, Polar and Desert Expeditions. *32nd International Conference on Environmental Systems*. San Antonio, Texas. , Society of Automotive Engineers. .
- BOTHMER, V. SOLAR CORONA, SOLAR WIND STRUCTURE AND SOLAR PARTICLE EVENTS. Kiel, Germany, Universität Kiel.
- BROWN, I. I., MUMMEY, D. & COOKSEYA, K. E. (2006) A novel cyanobacterium exhibiting an elevated tolerance for iron. *FEMS Microbiology Ecology*, 52.
- CANADA, G. O. (2006) *Biomining*, Canadian Government.
- CELESTIS Memorial Spaceflights Luna Services, Celestis Space Services Home Page.
- CENTER, N. A. R. (1988) Survey of Some Regenerative Physico-Chemical Life Support Technology. Moffett Field, California 94305, NASA Ames Research Center.
- CLEMENT, G. (2003) *Fundamentals of space Medicine*, Dordrecht, Kluwer Academic Publishers.
- COMMITTEE ON PLANETARY AND LUNAR EXPLORATION, N. R. C. (2002) *The Quarantine and Certification of Martian Samples*, Space Studies Board.
- CORPORATION, F. (2002) Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000.
- COUNCIL, C. O. P. A. L. E. S. S. B. D. O. E. A. P. S. N. R. (2002) *The Quarantine and Certification of Martian Samples.*, Washington, D.C., NATIONAL ACADEMY PRESS.

- COUNCIL, N. R. (1992) *Biological Contamination of Mars: Issues and Recommendations*, Washington D.C., Space Studies Board, National Academy Press.
- COVAULT, C. (2004) Inside the Bigelow Inflatable-Module Plant. *Aviation Week & Space Technology*.
- CRISTINA, S. R., VINADER, L. M. & WICHERS, H. (2000) Fungus on Orbit Demonstration.
- CROWTHER, E.-I.-C. G. L. C.-E. D. (1998) *Outlooks on Space Law over the Next 31 Years*, Netherlands, Kuwaer Law International.
- DAILY, D. I. (2005) ITAR Fallout: Britain to Pull Out of F-35 JSF Program? *Defense Industry Daily*.
- DARLING, D. *The Encyclopedia of Astronomy, Astrobiology, and Space Flight*.
- DAVID, L. (2000) Space Station Heats Up Cold War Rhetoric.
- DAVID, L. (2002) *Moon-Themed Casino: Place your bets*.
- DE DINECHIN, G. (1998) *Astronauts in Space: Liability and insurance Coverage*, International Space Brokers
- DIVISION, E. D. C. A. T. S. (2003) *Advanced Life Support Requirements Document*, Houston, Texas 77058, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center.
- DUDLEY-ROWLEY, M., WHITNEY, S., BISHOP, S., CALDWELL, B. & NOLAN, P. D. (2002) Crew Size, Composition, and Time: Implications for Habitat and Workplace Design in Extreme Environments. *AIAA, Space Architecture Symposium*. Houston, Texas, American Institute of Aeronautics and Astronautics, Inc.
- DUFFIELD, B. E. (2001) Advanced Life Support (ALS) Technologies List Version 4. 2400 NASA Road 1, P.O. Box 58561 Houston, Lockheed Martin Space Mission Systems & Services Science, Engineering, Analysis, and Test operation.
- DUSSAP, P. C. G. (2003) Technical Note 3: Definition of the Ideal Facility for Life Support Issues. *Review of European Ground Laboratories and Infrastructures for Sciences and Support of Exploration*. ESA.
- ECKART, P. (1994) *Life Support & Biospherics*, Muenchen, Germany, Herbert Utz Publishers.
- ECKART, P. (1996a) *Spaceflight Life Support and Biospherics*. Torrance, CA Boston, MA, Kluwer Academic Publishers.
- ECKART, P. (1996b) *Spaceflight Life Support and Biospherics. Microcosm Press Torrance,, California and Kluwer Academic Publishers*.
- ECKART, P. (1999) *The lunar base handbook: an introduction to lunar base design, development, and operations*, New York, McGraw-Hill.
- ELSON, P. (2006) Space Insurance and Risk Management. Aon Space, Aon Limited.
- ENERGY, U. D. O. (Feb-03) *Space Fission Reactor Power Systems: Their Use and Safety*.
- ESA (2000) After the gold Rush on Earth a 'Helium Rush' to the moon? *International Conference on Exploration and Utilisation of the Moon (ICEUM4)*
- ESA (2001) HUMEX, Study on the Survivability and Adaptation of Humans to Long- Duration Interplanetary and Planetary Environments. ESTEC.
- ESA (2006) Advanced Life Support - The Liquefying Compartment ESA.
- EXPLORATION, S. R. O. T. S. C. O. A. A. S. Space Handbook: Astronautics and Its Applications. Staff Report of the Select Committee on Astronautics and Space Exploration. *86th Congress, 1st Session, House Document, 86*.
- EXPLORATION, T. B. R. A. R. R. S. F. H. (2005) The Bioastronautics Roadmap: A Risk Reduction Strategy for Human Exploration. Space Life Sciences Directorate (SLSD), Johnson Space Center, NASA.
- FOAM, T. Texas Foam.
- FORSBERG, C. W., BURCHELL, T. D., WILLIAMS, D. E., HOLDAWAY, R. F. & QUALLS, A. L. (April 15th 2005), Oak Ridge National Laboratory.

- GAO (2006) GAO-06-817R Exploration Cost and Schedule. United States Government Accountability Office.
- GARY T. MOORE, E. A. (1992) Lunar Base Requirements for Human Habitability.
- GUGLIOTTA, G. (2006) U.S. Planning Base on Moon To Prepare for Trip to Mars.
- HADA, M. & SUTHERLAND, B. M. (2006) Spectrum of complex DNA damages depends on the incident radiation. *Radiat Res*, 165, 223-30.
- HARDING, R. M. (1989) *Survival in space: medical problems of manned spaceflight*, London, Routledge.
- HERMIDA, J. (2004) *LEGAL Basis for a National Space Legislation*, Netherlands, Kuwer Academic Publishers.
- HERODIN, F. & DROUET, M. (2005) Cytokine-based treatment of accidentally irradiated victims and new approaches. *Exp Hematol*, 33, 1071-80.
- HOLT, M. (2006) Nuclear Energy Policy. *CRS Issue Brief for Congress*.
- HORANYI, M., WALCH, B., ROBERTSON, S. & ALEXANDER, D. (1998) Electrostatic charging of Apollo 17 lunar dust. *Journal of Geophysical Research*, 103.
- HÖRL, E. M. (1961) Structure and Structure Imperfections of a Solid  $\beta$ -Oxygen. *Acta Crystallographica*, 15, 8.
- HW LANE, R. G., DA SCHOELLER, J DAVIS-STREET, RA SOCKI AND EK GIBSON (1997) Comparison of ground-based and space flight energy expenditure and water turnover in middle-aged healthy male US astronauts. *American Journal of Clinical Nutrition*, 4 to 12.
- INSTITUTE, Y.-N. H. T.
- IWASE, S. (2005) Effectiveness of centrifuge-induced artificial gravity with ergometric exercise as a countermeasure during simulated microgravity exposure in humans. *Acta Astronautica*, 57, 75-80.
- JONES, J. (2006a) Habitation.
- JONES, J. A. (2006b) *Muscles and Bones in Space*, Strasbourg, ISU SSP06.
- K. SCOTT, S. B. (2006) *Bundle Protocol Specification, Delay-Tolerant Networking Research Groups Draft Memo*
- KAISER, M. L. (2006) Solar Terrestrial Relations Observatory. Goddard Space Flight Center.
- KANGHAN, F. L., HANG YONGQIANG, LI JUNRONG (1995) Development of regenerative environmental control and life support system in space station.
- KENNEDY, C. (2006) Materials Scientist. Golden, Colorado, U.S.A.
- KLIEN, H. P. (1991) Planetary Protection Issues for the MESUR Mission: Probability of Growth (Pg). NASA Ames Research Center, Moffat Field, Calif., NASA.
- KLISS, M. (2006a).
- KLISS, M. (2006b) Life Support Systems For Human Space Exploration Beyond Low Earth Orbit. *Stanford University Lecture Series*, March, 7, 2006.
- KOELLE, H. H. (2000) Environmental Control & Life Support Systems (CELSS) for MOONBASE 2015. D-10587 Berlin, Marchstr.14, Technische Universität Berlin Institut für Luft- und Raumfahrt
- KOSUGE, T. (2005) Gakujutsuno Doukou. JAPAN, Zaidanhoujin Nihongakujutsukyoryokuzaidan.
- KUBICEK, K. & WOOLFORD, B. (1995) Man-Systems Integration Standards. NASA-STD-3000.
- LARSON, W. J. & PRANKE, L. K. *Human spaceflight mission analysis and design*, The McGraw-Hill Companies, Inc.
- LEWIS J. S., M. M. S., GUERRIERI M. L. (WITH 86 COLLABORATING AUTHORS) (1993) *Resources of near-Earth space*, Tucson US, London UK, The University of Arizona Press.

- LOVELOCK, J. E. *A New Look at Life on Earth*.
- MARINO, B. D. V., MAHATO, T. R., DRUITT, J. W., LEIGH, L., LIN, G., RUSSELL, R. M. & TUBIELLO, F. N. (1999) The agricultural biome of Biosphere 2: Structure, composition and function. *Ecological Engineering*, 13, 199–234.
- MARK AYRE, J. M. (2004) *HYPOMETABOLYPOMETABOLIC STASIS IN HUMANS FOR LONG DURATION SPACE FLIGHT*.
- MCPHEE, J. (2004) The International Multidisciplinary Artificial Gravity Project. Vancouver, Canada, 55th International Astronautical Congress
- MIT (2003) The Future of Nuclear Power. *Massachusetts Institute of Technology*.
- MOORE, G. T., PARULESKI, K. L., HUEBNER-MOTHS, J., FIEBER, J. P., REBHOLZ, P.J. (1992) *Lunar Base Requirements for Human Habitability*, NY, American Society of Civil Engineers.
- MPOWER, U. Mpower.
- MUKAI, C. (2006) The Heart in Space. Strasbourg, ISU SSP06.
- NAKAYAMA, N. & AL., E. Entomophagy; a key to space agriculture. NASA TransHab.
- NASA (2001) ISS Destiny (U.S. Laboratory Module) - Summary.
- NASA (2003a) *Columbia accident investigation Board report*, NASA.
- NASA (2003b) Guidelines and Capabilities for Designing Human Missions. NASA
- NASA (2005) *Exploration Systems Architecture Study Final Report*, USA, NASA.
- NASA (2006a) ARES - NASA new rockets get names. USA, NASA.
- NASA (2006b) NASA's Exploration Systems Architecture Study. IN WILSON, J. (Ed.), NASA.
- NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS, N. (2000) Recommendations of Dose Limits for Low Earth Orbit.
- O'BRYAN, M. The Natural Space Radiation Hazard. Goddard Space Flight Center.
- OFFICE, I. P. S. S. (2006) Environmental Monitoring of the International Space Station (Environmental-Monitoring). ISS Research, NASA.
- P.E., B. (2006) Resource extraction on the moon: Everything including the squeal. *Astrogeology: Moon, Mars and Beyond, 2006 AAPG Annual Convention*
- PANELS, S. L. P. Spectrolab.
- PAUL W. TODD, P. (2006) Chief Scientist. Greenville, Indiana, U.S.A.
- PEETERS, W. (2000) *Space Marketing: A European Perspective*, Microcosm, Inc. and Kluwer Academic Publishers.
- PEETERS, W. (2001) *Space Marketing: A European Perspective*, Toronto, Kluwer Boston, Inc.
- POMPIDOU, A. (2000) The Ethics of Space Policy. *UNESCO World Commission on the Ethics of Scientific Knowledge and Technology (COMEST) Working Group on the "Ethics of Outer Space"*
- PROJECT, I. M. S. T. (2006) Fertile Moon: Feasibility of Extraction of Resources and Toolkit for In-situ Lunar Exploration. Strasbourg, France, International Space University.
- RAPP, D. (2005) Radiation Effects and Shielding Requirements in Human Missions to Moon and Mars. *MARS*, 1 to 6.
- RAPP, D. (2006) *Lunar ISRU - Love it or Leave it!*
- REAMES, D. V., BARBIER, L.M., NG, C.K. (1996) The Spatial Distribution of Particles Accelerated by CME-Driven Shocks. *Astrophysics Journal*, 466, 473-486.
- RESORTS, M. W. Moon World Resorts homepage.
- SADEH & AL., E. (2005) Public-private models for lunar development and commerce. *Space Policy*, 25, 267-275.
- SADLER, P. (2006) Zubrin, R., University of Arizona.



- SCHMITT, H. H. (2004) *Geology of Lunar Helium-3: Helium concentration in undistributed regolith*, Golden Colorado, University of Wisconsin-Madison.
- SCHMITT, H. H. (2006) Production of Lunar Helium 3 Energy Resources. *Astrogeology: Moon, Mars and Beyond*.
- SCIENCE, C. I. S. Priorities in Space Science Enabled By Nuclear Power and Propulsion. 500 Fifth St. Washington D.C., The National Academic Press.
- SCOTT R. WITHERSPOON, S. T., AND LARRY A. ROE (2001) Development of a MEMS-based health-monitoring module for space inflatable structures *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit*. 42nd, Seattle, WA, Arkansas, Univ., Fayetteville.
- SCWARTZKOPF, S., HOULE, J. & GUSTAFERRO, A. (1991) Lunar Base Controlled Ecological Life Support (LCELSS): Preliminary Conceptual Design Study. Lockheed Missiles & Space Company.
- SHAYLER, D. L. (2000) *Disasters and Accidents in Manned Spaceflight*, Praxis Publishing.
- SHIMP, T. A. *Advertising and Promotion*, California, USA, University of South California.
- SMITH, M. (2004) *Space Exploration; Overview of President Bush's "Vision for space exploration," and Key issues for congress*, USA, CRS.
- SMITHSONIAN, N. A. A. S. M. Saturn V: America's Moon rocket. Smithsonian National Air and Space museum.
- SOCIETY, N. S. (2006) NSS Statement of Philosophy.
- STANFORD, M. & JONES, J. A. (1999) Space radiation concerns for manned exploration. *Acta Astronaut*, 45, 39-47.
- STATE, U. S. D. O. (2006) ITAR, U.S. Department of State, Directorate of Defense Trade Controls.
- STEVEN J. ISAKOWITZ, E. A. (2000) *INTERNATIONAL REFERENCE GUIDE TO SPACE LAUNCH SYSTEMS THIRD EDITION*, USA, AIAA.
- STOKER, C. R. & EMMART, C. (1996) *Strategies for Mars: a guide to human exploration*, San Diego, California 92198, Science and technology series (AAS).
- STUBBS, T. J., VONDRAK, R. R. & FARRELL, W. M. (2005) Impact of Dust on Lunar Exploration. *'Dust in planetary systems'*. Kaua'I, Hawaii, Lunar and Planetary Science XXXVI. Proc. Conf
- SUZUKI, D. T. (1993) *Time to Change: essays*, Australia Allan & Unwin.
- SWISHER, C. E. K. R. L. (2005) Cost Analysis of Solar Reflective Hard-Coat Materials Deposited by Ion-Beam-Assisted Deposition. *Journal of Solar Energy Engineering*, 127, 7.
- SZOKA, B. (2006) National Security Case for ITAR Reform *25th Annual International Space Development Conference*. Los Angeles, California, The National Space Society.
- TAKIZAWA, K. (1987) *Uchuuhou System JAPAN*, Koujinsha.
- TASK GROUP ON THE FORWARD CONTAMINATION OF EUROPA SPACE STUDIES BOARD COMMISSION ON PHYSICAL SCIENCES, M., AND APPLICATIONS NATIONAL RESEARCH COUNCIL (2000) Preventing the Forward Contamination of Europa. Washington, D.C., NATIONAL ACADEMY PRESS.
- TAYLOR, L. A., SCHMITT, H. H., CARRIER, W. D. & NAKAGAWA, M. The Lunar Dust Problem: From Liability to Asset. *American Institute of Aeronautics and Astronautics*.
- TECH, S. A. (2001) *Atlas V - Specifications*.
- THE GALLUP ORGANIZATION, I. (2005) *Space Exploration Survey*, Princeton, The Gallup Organization Inc.
- THOMAS, M. Inflatable space structures.

- THORPE, A. (2003) *The Commercial Space Age: Conquering Space Through Commerce*, 1st Books.
- TOLYARENKO, P. N. (2006) Environmental Control & Life Support System. Strasbourg, International Space University.
- TRIBBLE, A. C. (1995) *The Space Environment: Implications for Spacecraft Design*, Princeton, New Jersey 08540, Princeton University Press.
- VAN ONCK, A. (2006) Ergonomic modules for the human body? *Design Language etc.*'
- VERSHOOR, D. (1999) *An introduction to space law*, Netherlands, Kuwer Academic Publishers.
- VICENTE, K. J. (1999) *Cognitive work analysis: Toward safe, productive, and healthy computer based work.*, Mahwah, NJ, Lawrence Erlbaum.
- WADE, M. (1997 - 2006) Lox/LH2. *Encyclopedia Astronautica*.
- WERTZ, D. J. (Spring 2005) *Design of Low-Cost Space Missions*, El Segundo, CA, MICROCOSM, INC.
- WHEELER, R. M., SAGER, J. C., PRINCE, R. P., KNOTT, W. M., MACKOWIAK, C. L., STUTTE, G. W., YORIO, N. C., RUFFE, L. M., PETERSON, B. V., GOINS, G. D., HINKLE, C. R. & BERRY, W. L. (2003) Crop Production for Advanced Life Support Systems. TM-2003-211184. NASA.
- WHITE, W. (1997) Real Property Rights in Outer Space. *American Institute of Aeronautics and Astronautics*.
- WIELAND, P. O. (1994) Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems. George C. Marshall Space Flight Center, Alabama, NASA.
- WILSON, T. L. & WILSON, K. B. (2005) Regolith Sintering: A Solution to Lunar Dust Mitigation? Kaua'I, Hawai, Lunar and Planetary Science XXXVI. Proc. Conf 'Dust in planetary systems'.
- WINGATE, S. Moon Anomalies from Clementine.
- WITHERSPOON, S. R., TUNG, S. & ROE, L. A. (2001) Development of a MEMS-based health-monitoring module for space inflatable structures *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit*. 42nd, Seattle, WA, Arkansas, Univ., Fayetteville.
- WORDEN, S. P. (2006) The Vision for Space Exploration: new opportunities – A speech by NASA ARC Director Simon P. Worden?. *International Space Development Conference*. Los Angeles.
- ZABEL, B., HAWES, P., STUART, H. & MARINO, B. D. V. (1999) Construction and engineering of a created environment: Overview of the Biosphere 2 closed system. *Ecological Engineering* 13 (1999) 43–63.
- ZELNIO, R. (2006a) The effects of export control on the space industry. *The Space Review*.
- ZELNIO, R. (2006b) A model for the international development of the Moon. *The Space Review*.
- ZURR, I., CATTS, O. (2004) *The ethical claims of Bio Art: killing the other or self-cannibalism?*



**INTERNATIONAL SPACE UNIVERSITY**  
1, Rue Jean-Dominique Cassini  
67400 Illkirch-Graffenstaden  
FRANCE



<http://www.isunet.edu>