

FUTURE HUMAN SPACEFLIGHT: THE NEED FOR INTERNATIONAL COOPERATION



International Academy of Astronautics



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Study on FUTURE HUMAN SPACEFLIGHT: THE NEED FOR INTERNATIONAL COOPERATION

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**IAA 50th Anniversary
Heads of Space Agencies Summit**

**Human Spaceflight Study Group
IAA Study**



**Editors
Scott Pace
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Foreword

I am pleased to welcome the present International Academy of Astronautics (IAA) study that will support discussions during the historic Heads of Space Agencies Summit on November 17, 2010 in Washington DC, USA. Prepared during a record time of one year with an unprecedented support, this study constitutes one of the four pillars of the Summit dialogue.

In addition four successful IAA conferences contributed to the input of the four studies, namely: the Academy Day in Bremen on planetary robotic exploration, the IAA conference in Riga on disaster management, IAA conference in Nagoya on climate change and the Academy Day in Prague on human spaceflight.

I would like to thank the Study group members who have prepared this study and the Trustees of the Academy who have reviewed it. I would like to particularly thank the Summit Coordinator, Dr. Jean-Michel Contant, IAA Secretary General, who has coordinated these four studies and remarkably secured the 25 Heads of Space Agencies, as of October 17th, 2010.

I would like also to extend my thanks the Co-Chair of the Steering Committee and Summit Program Manager, Mrs. Corinne Jorgenson, President, Advancing Space and the Co-Chair of the Steering Committee, Mrs. Mary Snitch, Director, Lockheed Martin Corporation for their valuable contributions to the studies and Summit preparation.

After 50 years of existence the International Academy of Astronautics is recognized by space agencies as a unique elite body that can help advancing international cooperation. It has been observed that much current cooperation programs are aging such as the International Space Station (ISS) initiated with just a few countries. Many newcomers are joining the club of emerging space countries and more than half of the current space agencies did not exist at the beginning of ISS. The result is a need to enlarge significantly the circle of the current partners for international space cooperation.

The IAA with members from all over the world is engaged in extending the frontiers of knowledge in space exploration and also its applications to solve the day-to-day problems of humankind. Academicians have worked in unison to achieve the set goals of the Academy and it is inspiring to note the many IAA emerging activities. In view of the Summit achieving successful concrete preliminary results, many space agencies have already welcomed the Academy serving as catalyst for years to come with several subsequent implementation meetings and studies.

Gopalan Madhavan Nair
President International Academy of Astronautics

Executive Summary

With the successful completion of the International Space Station and the establishment of a coordination framework under the Global Exploration Strategy, it is timely for the world's space agencies to assess their common interests and objectives for human space exploration, taking into account the foundation of the International Space Station and looking to human explorations beyond the Earth.

This International Academy of Astronautics (IAA) Human Spaceflight Study Group report, written by a truly international team, is an end-to-end assessment of the Human Spaceflight issues starting from the basic exploration questions, and ending with possible international cooperation implementation schemes. This Study provides concrete proposals on how to move beyond the International Space Station program and to make Human Spaceflight part of a broader international agenda for the benefit of all mankind.

This Study supports and remains consistent with the Global Exploration Strategy. It is not a proposal for a single program, but an approach that recognizes that individual space exploration activities can achieve more through coordination and cooperation.

The time horizon used by the Study Group is from the present day through 2050. This time horizon is meant to look toward the needs of the next generation of scientists, engineers, and other members of the international space community. It is sufficiently long to look beyond immediate political conditions but not so far as to be beyond practical planning. For the foreseeable future, the Low Earth Orbit (LEO), the Moon, Mars and near-Earth asteroids are the primary targets for human space exploration. But exploring even the first group of feasible destinations will require both robotic and human missions of all sizes and complexities.

Many new technical and engineering achievements will be necessary to move forward until 2050. In particular, technologies in space propulsion will need to include nuclear rocket engines or other means that would enable humans to travel long distances two to three times faster than with chemical propulsion. Long duration space radiation protection, highly reliable, closed or semi-closed life-support systems, on-board crew physical training to combat deconditioning, and new means of compact food generation will be needed. All of these new capabilities may have to be integrated into one or more large space transportation complexes in Low Earth Orbit before embarking on deep space voyages.

Most space organizations, both governmental and commercial, have struggled with answering the question of why we should invest the considerable resources necessary for human space exploration. This Study Group report believes that human space exploration can and should be guided by questions that promote international collaboration and cooperation, even if the other questions may still play a role. The ultimate objective of space exploration is to extend human presence across the Solar System and create sustainable

communities beyond the Earth. Human space exploration is the only approach to achieve that ultimate objective or to even answer whether such a future is in fact possible. Through cross-disciplinary comprehensive study and exploration, humanity will be able to explore deeper into the unknown, acquire a better understanding of the universe and the Earth, and secure benefits for future generations.

Although space exploration, and human space exploration in particular, is a discretionary activity, it has several strategic benefits. It is the most interdisciplinary of human activities, drawing on every field of science and technology, medicine, and even the social sciences, to achieve capabilities never before demonstrated. Human spaceflight is an emblematic endeavor and has therefore become an element of the political agenda of a growing number of countries worldwide. The success of international projects involving human missions to LEO helps to build confidence and a willingness to consider more ambitious cooperative missions beyond LEO. In this light, participation in Human Spaceflight programs should be also extended to countries that have not yet approved those programs but are interested in related education and technology development.

The International Space Station is the largest, most complex, and most international engineering project ever undertaken. It has been a diplomatic and technical success and with the completion of the assembly phase, the Partners' utilization efforts will determine whether it will be a global research success. The time is now to reap benefits by utilizing the ISS to its fullest extent for improving life on Earth, not only in the classical areas of microgravity materials science, biology, and fluid physics but also in new applications such as exploration technology test beds and climate change monitoring. The ISS is an extremely valuable existing orbital asset that serves as the foundation infrastructure for human spaceflight and thus it should be exploited as fully as possible.

The expansion of humankind's presence beyond LEO should be done in a careful, stepwise manner. The establishment of a human outpost beyond LEO is one logical next step while shorter duration missions could explore specific areas of the Moon and evaluate the potential for local, man-tended facilities. The proximity of the Moon for technology development, planetary operational experience, and the investigation of intriguing lunar science questions are strong arguments for such efforts prior to attempting human landings on Mars. In addition, human missions to low gravity bodies such as asteroids and the Martian moons provide practical destinations for gaining deep space operational experience and scientific discovery prior to human landings on Mars. All of these efforts should be supported as much as possible by robotic means as both pathfinders and complementary support for human missions.

Future possible mechanisms for international cooperation in human space exploration should be based on the ISS "lessons learned" to date and utilize existing mechanisms such as the International Space Exploration Coordination Group (ISECG). The ISECG

fosters voluntary, nonbinding international coordination in space exploration among space agencies.

The long-term sustainability of worldwide space exploration programs will benefit from the participation and support of a broader community outside of the current space industry, including financial and logistical support, and the inclusion of the public through a variety of measures targeted at a non-specialist audience. The involvement of existing, emerging, and developing space nations in such endeavors will both strengthen existing partnerships and foster new ones.

A future global space exploration program should be designed to fulfill future expectations of many stakeholders, including the public, and draw on the experiences of all existing mechanisms. Additional mechanisms may be needed, however, to coordinate political support for efforts that are broader than the ISS partnership while realistically reflecting current space capabilities. To this end, human space exploration will be more effective and beneficial if planned and conducted with international cooperation in mind from the beginning. Such efforts represent a transition from the competitive beginnings of human spaceflight to one of routine and comprehensive cooperation. Just as Russia joining the International Space Station was a powerful symbol of the end of the Cold War, so too would the joining of China, India, and others with the ISS partners in a cooperative effort to explore the Moon, Near Earth Objects and Mars be a powerful symbol of hope for the 21st Century.

Given the strategic and societal importance of Human Spaceflight, consideration should be given to holding a Heads of Agency meeting in conjunction with G-20 meetings to review major space exploration initiatives and bring this topic to the political agenda of the participating Ministers and Heads of State.

The recommendations for the priority areas of international cooperation are:

- Develop an integrated architecture for LEO and beyond including all human space-faring nations.
- Define/develop a common transportation policy for LEO and beyond
- Define/implement common interoperable standards for human spaceflight missions
- Define/coordinate champion countries for specific technologies amongst the human spaceflight countries
- Define/develop an integrated Human Spaceflight Space Situational Awareness system
- Define/develop an integrated public engagement plan for human spaceflight
- Coordinate research on Human Factors
- Foster opportunities for as many countries as possible to participate in human spaceflight activities in view of its strategic and societal importance for humanity.

1. Introduction

In the past 50 years, space capabilities have become essential to a wide range of critical national and international interests, from the global economy and international security, to scientific research and environmental monitoring. Since the end of the Cold War, however, the role of human spaceflight continues to be debated in part due to concerns with its costs and the fact that only a few nations have demonstrated independent human spaceflight capabilities. With the successful completion of the International Space Station and the establishment of a coordination framework under the Global Exploration Strategy¹, it is timely for the world's space agencies to assess their common interests and objectives for human space exploration, taking into account the foundation of the International Space Station and looking beyond to human explorations of the Moon, Mars and other locations beyond the Earth.

¹ <http://www.globalspaceexploration.org/>

2. Objectives

This International Academy of Astronautics (IAA) Human Spaceflight Study Group report, written by a truly international team, is an end-to-end assessment of the human spaceflight issues starting from the basic exploration questions, and ending with possible international cooperation implementation schemes. This Study provides concrete proposals on how to move beyond the International Space Station program and to bring the human spaceflight activities to the agenda of the G-20 meetings, making it a truly global undertaking for the benefit of all mankind. The International Academy of Astronautics is taking the lead in this effort and the IAA 50th Anniversary Heads of Space Agencies Summit in November 2010 is the first step in this direction.

This IAA Human Spaceflight Study Group report supports and remains consistent with the Global Exploration Strategy and its associated voluntary, non-binding coordination mechanism in which nations can share plans for space exploration and collaborate to strengthen both individual projects and the collective effort. This approach is not a proposal for a single program, but recognizes that individual space exploration activities can achieve more through coordination and cooperation. For the foreseeable future, the Low Earth Orbit (LEO), the Moon, Mars and near-Earth asteroids are the primary targets for human space exploration. But exploring even the first group of feasible destinations will require both robotic and human missions of all sizes and complexities.

This IAA Study is based on the contributions of the individuals listed in Appendix 1. Its content is based on the personal views of the participants, not that of the organization they work for.

3. Scope and Boundary Conditions

This report of the Human Spaceflight Study Group has sought to identify the required enabling technologies, including robotic missions, for human space exploration beyond Low Earth Orbit. In a complementary manner, the Planetary/Lunar Exploration Study Group concentrated on science-driven, robotic missions. Science-driven missions are defined as those that are conducted in response to science community priorities, such as those defined in the US by decadal surveys by the National Academy of Science and open to the international scientific community, as well as in Cosmic Vision by the European Space Agency and by similar reports in other countries. Both Study Groups seek to promote technical standardization and interoperability in common infrastructures, e.g. space communications, navigation, and power systems.

The time horizon used by the Study Group is from the present day through 2050. This time horizon is meant to look toward the needs of the next generation of scientists, engineers, and other members of the international space community. It is sufficiently long to look beyond immediate political conditions but not so far as to be beyond practical planning. This time horizon can be divided into two or three shorter intervals that potentially overlap with each other:

2010-2025 – This period is characterized by International Space Station (ISS)-based human spaceflight, one or more additional laboratories in Low Earth Orbit (LEO) with international participation, and the development of capabilities and technologies necessary for beyond LEO missions.

2020-2035 – This period is characterized by the maturation of LEO assembly capabilities that directly support explorations beyond LEO, for example to the Moon and near-Earth asteroids. Robotic precursor missions further develop the capabilities for human missions beyond LEO. The first human missions to Lagrange points, cis-lunar space and a Near-Earth Object take place.

2030-2050 – This period is characterized by human space exploration missions beyond the Moon, for example to the Martian Moons, Mars itself, and perhaps beyond.

Many new technical and engineering achievements will be necessary to move forward in each of these time periods. In particular, technologies in space propulsion will need to include nuclear rocket engines or an alternative propulsion system that enables humans to travel long distances two to three times as fast as current chemical propulsion techniques. Long duration space radiation protection, highly reliable, closed or semi-closed life-support systems, on-board crew physical training to combat deconditioning, and new means of compact food generation will be needed. All of these new capabilities may have to be integrated into one or more large space transportation complexes in Low Earth Orbit before embarking on deep space voyages.

Space activities should be conducted with the intent of exploring, developing, and utilizing space and non-terrestrial resources beyond the Earth. Exploration experiences are the fundamental foundation for future decisions regarding space development and utilization. Both robots and humans have unique and necessary roles in human exploration of the universe and in improving our awareness of the Earth and ourselves as human beings. International cooperation is desirable for many reasons, but first to avoid waste and repeating mistakes, to increase safety and to maximize benefits for all humanity. It can be expected that multi-disciplinary and comprehensive approaches to space research and exploration will continue to grow and become even more important in the future.

To these ends, the framework of the Global Exploration Strategy can be used as a guideline for a global human exploration strategy. The aspirations of the new space exploration era will require a governance structure that not only enables non-binding coordination among space agencies but an efficient planning and decision-making process that represents all exploration stakeholders.

4. Exploration Questions

When people think or talk about human space exploration, they generally focus on destinations that can be reached by humans, such as the Moon, Mars, and near-Earth asteroids. Engineers and technical people like to dwell on the performance questions of how fast, how high, how big, and how long. Program managers naturally worry about how much these efforts will cost and how long they will take. All of these who, what, where, and when questions related to space exploration miss the most fundamental question of “why?”

Most space organizations, both governmental and commercial, have long struggled with answering the question of why we should invest the considerable resources necessary for human space exploration. Also missing from this discussion is the answer to why the risk of human life in this endeavor is warranted. Until we address the fundamental question of why, it will be difficult to establish a successful and sustainable program of human space exploration. Answering this question is key to obtaining the public and political support needed for a challenge of this magnitude.

In the past, space exploration in the form of the Apollo journeys to the Moon was motivated by questions of political and military competition. What are the questions that will motivate human space exploration today and in the future? This Study Group report believes that human space exploration can and should be guided by questions that promote international collaboration and cooperation, even if the other questions may still play a role. To that end, motivating questions should be both simple, but profound, with implications for all of humanity. Perhaps the foremost question we can ask is whether humanity will have a future beyond the Earth? The answer may be “yes” or “no,” and only actual experience will provide the answer.

It can be argued that the purpose of human space exploration is ultimately to answer the question of whether humans have a future beyond the Earth and if so, what kind of future that might be. This question is every bit as profound as the search for life beyond the Earth or efforts to answer the most fundamental scientific questions. Some of these questions, such as whether extended human occupation of Mars would be possible, may not fall within the time horizon of this report. The important factor is not just particular destinations but also what the most important questions to be addressed by exploring those destinations with humans are.

There are two questions, the answers to which lead to very different human destinies in space. The first is: “Can extraterrestrial materials be used to support life in locations other than Earth?” And the second is “Can activities of sustained economic worth be carried out at those locations?”² Or as it might be expressed more compactly: “Can we live off the land?” and “Can we make it pay?” If the

2 *Harry L. Shipman, “Humans in Space: 21st Century Frontiers,*
” Plenum Press, 1989

answer to both is yes, we will see space settlements and the incorporation of the expansion of the global economy to include non-terrestrial resources. If the answer is no, then space is a form of Mount Everest – a location for personal challenge and tourism but not the location of a human community. Other answers might remind us of Antarctica or perhaps an off-shore oil platform tended from land.

Many people believe they already have answers to these questions, but in reality the answers are unknown at this time. Therefore our efforts should be to answer these questions in the course of human and robotic explorations beyond the Earth. The quest to do so will teach us much of practical benefit as we seek to do things that are hard to achieve. The experiences we gain will give us new insights into who we are. This might seem like a circular argument; however, considering the nearly limitless benefit offered by human spaceflight, it is reasonable that nations “invest” in their future, taking into account that as any investment it also presents risks.

Where can humans explore, live, and work? There are many places in the solar system where only robots will go with any foreseeable levels of technology. However, it is not clear where humans will be able to go. Certainly the Moon and Near-Earth Objects, probably Mars, but how about the Moons of Jupiter and Saturn? Can humans survive and work for extended periods without re-supply from Earth? In the longer term, are there sustainable economic reasons for a permanent human presence or even a community in space? Many advocates of human space exploration claim space settlements are desirable and inevitable, but objectively we cannot know without actual experience.

Necessity of Humans in Deep Space Exploration

As space exploration extends farther into the solar system, the problem of communications signal delays becomes so severe that it is difficult to conduct complex explorations with unmanned vehicles controlled from Earth. Even currently advanced robots, such as the Mars Exploration Rover, required continuous human attention and control from Earth. For future complex and cross-disciplinary missions, trained astronauts can resolve many technical difficulties by being on-site and thereby improve the probability of mission success. Moreover, human presence, with the accompanying human intelligence, is the most valuable asset to increase and enhance the scientific and technological results beyond what is planned.

Research on human adaptation and countermeasures to spaceflight is an important aspect of space exploration and a challenge that must be addressed if long-term exploration objectives are to be achieved. It is only through human spaceflight that actual data about human adaptability to microgravity, space radiation and so

on can be obtained for the development of knowledge in the space life sciences. Efforts are needed to improve the data return from the relatively small number of persons with spaceflight experiences as well as find better ground-based analogs for research.

As part of answering the question of whether humans have a future beyond the Earth, and if so, what kind of future, humans and robots will have necessary and complementary roles. Robots will serve as pathfinders for human expeditions to accessible destinations and journey to places too dangerous for humans. Humans will be necessary in order to respond to local challenges and the unexpected while also serving to push the development of more capable machines to extend our reach to the knowledge and resources that lie beyond the Earth.

Cross-disciplinary Comprehensive Research

Successfully conducting space exploration involves mastery of multiple technical subjects, including physics, space astronomy, space chemistry, space geology, space life sciences and so on. Space physics studies physical phenomenon in space. Space astronomy is to utilize space vehicles to conduct astronomical observation and research outside the Earth atmosphere. Space chemistry studies chemical processes as well as chemical composition and evolution of cosmic substances in the space. Space geology studies the physical composition, structure and formation and evolution history of celestial bodies such as the Moon, planets and their moons. Life sciences study life phenomena in space and explore life beyond the Earth.

While these fields have terrestrial foundations, they have all been enriched by exposure to new information and experiences resulting from spaceflight. In particular, human spaceflight has spurred research in space physiology, space biology, space medical science and life support systems and has proven to be an effective stimulant to learning when new scientific knowledge is needed in real world situations. The complexity of issues related to human spaceflight tends to require “non-traditional” approaches across multiple disciplines and this helps foster new discoveries and innovation.

Common National Goals and Objectives

The current national space exploration programs of major space-faring countries address many common goals and interests, e.g., science, economic expansion, and the spirit of society for new endeavors. The table below summarizes primary examples of short and long-term goals for space exploration.

Table 1. Short and long-term goals and objectives of space exploration³

Goal and objectives	Short-term	Long-term
Explore the universe (Origins, search for life)	Secure scientific participation and components for all current and future space activities	Conduct a program that balances scientific and technological advances in space exploration
Strategic Partnerships	Foster non-binding agreements in space exploration in the near term. Form strategic alliances that provide synergies.	Build a global space exploration program that is conducted in cooperation with many countries/ stakeholders under binding rules.
Space technology supporting Earth sciences	Prioritize space activities that help to better understand Earth and that can bring benefit to humans	Conduct space endeavors in synergy with Earth sciences and develop infrastructures that help to solve imminent problems
Innovative technology	Develop technologies that can lead to breakthroughs for material sciences, transportation, health care, etc.	Foster innovative technology programs between aerospace companies and non-space industries with high spin-off potential
Commercial expansion	Support and foster commercial space activities	Create synergies with governmental space programs
Inspire the public	Close the gap of public unawareness of space exploration	Build global public relations initiatives and education programs
Extend human presence	Prepare activities for human space transportation systems and related science and technology capabilities	Human space travel to the Moon and later to Mars. Construction of habitats and infrastructures in space

New avenues provided by the expanding roles of new or current stakeholders (e.g. new services from the space industry) will strengthen future human exploration plans. Long-term planning and development of major space architectures for exploration can only succeed when all stakeholders -governments, space agencies, science community, commercial space sectors, space entrepreneurs, and the public- can work toward common, or at least synergetic, goals at national and international levels.

The coming era of space exploration will include, apart from research on the International Space Station, human missions to the Moon, Mars, and near-Earth asteroids. While science and technology represent the core and, often, the drivers for space exploration activities, human exploration is a multi-stakeholder endeavor that involves several other disciplines. A shared vision is thus crucial to provide direction that enables new countries and stakeholders to join and engage in an overall effort. This report touches briefly on high-level goals and objectives in each of the next major areas of human space exploration, starting in LEO and moving outward.

International Cooperation in Human Spaceflight

As globalization has advanced, leading space countries have established space development strategies and invested significant funds to independently implement their respective space plans according to their own space objectives, technical capabilities, and national situations. On the other hand, many countries are actively collaborating, seeking common interests, and sharing knowledge and experiences to maximize the benefits from their respective space efforts.

International cooperation in human spaceflight is continuing to develop as political conditions for cooperation improve and ordinary collaborative programs are upgraded to more strategic levels. Collaboration on the design and development of human space missions is increasing gradually as space agencies are able to agree on common standards and interface protocols. The success of international projects involving human missions to LEO helps to build confidence and a willingness to consider more ambitious cooperative missions beyond LEO.

Participation in human spaceflight programs should be also extended to countries that have not yet approved those programs but are interested in related education and technology development.

International Space Station

The International Space Station is a model program of international cooperation, which is joined by 16 countries for construction and operation and integrated by advanced facilities and technology from increasingly capable space countries. Research on the International Space Station is delivering increasing science returns

as summarized in the report: “International Space Station Science Research: Accomplishments during the Assembly Years: An Analysis of Results from 2000-2008 (Evans et al. 2008).” The increase in facilities, a larger crew, and better-equipped laboratories offer an environment to successfully prepare for human exploration. A NASA (National Aeronautics and Space Administration) Decadal survey on “Life and Physical Sciences Space Research” is currently investigating research objectives that define and align life and physical sciences research to meet the needs of exploration missions.

The European Programme for Life and Physical Science in Space (ELIPS) makes the European Space Agency (ESA) one of the largest scientific users of the ISS at present. Among the future ESA research objectives is the “Preparation of Human Exploration of Space” with a focus on radiation biology and physiology, life support systems, food production, material testing. Several laboratories including MISSE (Materials International Space Station Experiment), the U.S. Laboratory Destiny, the European Laboratory Columbus, the Russian greenhouse LADA, the Japanese Experiment Module “Kibo” can perform key investigations for human exploration during the next decade.

Human Exploration of the Moon

Science roadmaps and recommendations for lunar exploration have been produced by an array of national and international working groups. Such studies highlight the most compelling aspects of fundamental and applied scientific imperatives related to the exploration of the Moon and together they comprise a touchstone for space exploration that can enable architectural studies for human and robotic exploration. Forging a partnership between robotic science and human exploration can help provide a unified long-range vision for planetary exploration. The International Space Exploration Coordinating Group (ISECG)⁴ Reference Architecture for Human Lunar Exploration has been developed as a concept to envision how the Moon could be collaboratively explored, using coordinated assets from many agencies, and thereby informing preparatory planning and decision-making within participating agencies. It represents a concrete step towards realizing the vision of the Global Exploration Strategy.

The International Lunar Exploration Working Group (ILEWG) advances work in the areas of lunar science exploration, living and working on the Moon, key technologies, utilization of lunar resources, infrastructure of lunar bases, surface operations. The Lunar Exploration Analysis Group (LEAG) has constructed a Lunar Exploration Roadmap (LER), and serves as a community-based, interdisciplinary forum for future exploration and provides analysis in support of lunar exploration objectives and their implications for lunar architecture planning and activity prioritization.

⁴ *This group was set up in late 2007 to implement the Global Exploration Strategy.*

Human Exploration of Mars

Human exploration of Mars is likely several decades away, but in-situ exploration by humans could lead to a deeper understanding of the evolution of the solar system and the origin and evolution of life. The international Mars Architecture for the Return of Samples (iMARS) Working Group was chartered by the International Mars Exploration Working Group (IMEWG) in mid-2006 to develop a potential plan for an internationally sponsored and executed robotic Mars sample return (MSR) mission, an important precursor mission to future human activities on Mars.

The “Preliminary Planning for an International Mars Sample Return Mission” report was published in March 2008.

The Mars Exploration Program Analysis Group (MEPAG) represents a forum designed to provide science input for planning and prioritizing Mars future scientific activities for the next several decades. The MEPAG Goals document summarizes a consensus-based list of broad scientific objectives organized into a four-tiered hierarchy: goals, objectives, investigations, and measurements. The fourth goal of MEPAG’s roadmap is dedicated to the “Preparation for human exploration.” To support the development of an integrated human/robotic science strategy and human exploration of Mars, MEPAG will address new topics in the near future to determine: (i) the properties of the Martian surface and whether that could affect surface operations by humans on Mars, (ii) whether Martian environments entering in contact with humans are reasonably free of biohazards to humans, and (iii) potential sources of water and other materials as a resource (In Situ Research Utilization) for human missions.

Human exploration of Near-Earth Objects (NEOs)

The combination of the diversity and accessibility of Near-Earth Objects presents new opportunities and challenges for space exploration. The current NASA space exploration roadmap envisages a visit by humans to an asteroid around 2025. For both applied and fundamental science, a human NEO mission would produce a wealth of data, at the same time expanding the human spaceflight experience base beyond Low Earth Orbit and the Earth-Moon system, proving space-qualified hardware directly applicable to lunar and Mars exploration. The 1998 U.S. National Research Council study entitled “Exploration of Near-Earth Objects” (NRC 1998) defined several applied science goals including: (i) understanding the NEO surface physical properties so as to allow the design of systems that impact, or attach to these surfaces, (ii) determining the diversity of objects within the NEO population with respect to mechanical and bulk properties, (iii) calibrating Earth-observations to remotely determine the essential physical properties of NEOs. An astronaut Extra-Vehicular Activity (EVA) to the surface of an NEO could also provide an important public outreach and demonstration relevant to defending Earth from NEO Collision.

5. Global Political Context

Space activities are facing challenges common to all government-led efforts, notably global economic and technical competition and pressing financial needs for domestic economic and social development. Global challenges such as climate change, disasters and natural hazards, and international security have higher priorities than human activities in Low Earth Orbit and the exploration of the solar system. Although space exploration, and human space exploration in particular, is a discretionary activity, it has several strategic benefits. It is the most interdisciplinary of human activities, drawing on every field of science and technology, medicine, and even the social sciences, to achieve capabilities never before demonstrated. Human spaceflight is an emblematic endeavor and has therefore become an element of the political agenda of a growing number of countries worldwide.

While the first decades of space exploration were dominated by a duopoly of the USA and the USSR, the geopolitics of space activities has evolved considerably in the last decades. The rising number of new countries embarking on space exploration activities provides evidence of the internationalization and globalization of space exploration. Stakeholders such as industries, non-governmental organizations, transnational companies and the public will be more involved in the future planning and execution of space activities. In this evolving context, the case for increasing consideration of cross-cultural management in space exploration activities, particularly among the main space powers, the United States, Russia, Europe, Japan, Canada, China and India, will thus be a key to long-term sustainable human and robotic space exploration endeavors.

International cooperation potentially makes the implementation of human space exploration more affordable to each individual partner involved, while also enriching the pool of scientific and technological expertise. Access to alternative transportation systems and redundancy through added mission options offer robustness and sustainability for space exploration. The ISS is the most applicable example for international space exploration to date and represents a major milestone that will shape future international space partnerships and exploration in particular.

Participation in successful human space exploration missions requires the most advanced levels of systems engineering, quality control, and skilful management. These capabilities are still possessed by a relatively small number of countries. The U.S. and Russia have well established capabilities in launch systems, robotic exploration and human spaceflight. China has recently demonstrated human spaceflight capabilities. Japan and Europe are well advanced in their exploration capabilities as well but have not yet invested in autonomous human spaceflight capabilities. Canada continues to nurture its robotic capabilities and is reinforcing its astronaut corps. Current space participants have the potential to complement each other in collaborative efforts to explore targets in our solar system with humans. The

development of new capabilities by rising space powers like China and India will allow a global exploration program with a higher frequency and diversity of human exploration missions.

Currently, only three governments have the independent capability of launching astronauts into LEO: the United States, Russia and China. The new directions for NASA proposed on the occasion of the release of the FY2011 budget request (presented in February 2010) indicate a desire for a paradigm shift for NASA's human spaceflight program that will in the future rely more on substantial support from the commercial sector for carrying crews to LEO, while government activities will focus on taking humans beyond Earth orbit. The idea of private, commercial space access has been around for decades. However, it will be a challenge to make human spaceflight a commercial practicality.

With the completion of ISS construction it is expected that the ISS Partners would consider new participants such as China, India, and South Korea. Additional participants would create new management challenges but they will provide additional logistical resources to support wider utilization. The means are already in place (e.g. the Non-Partner Process) among the ISS program participants to have experiments from non-Partner countries using ISS scientific facilities and logistics support and crews arriving from non-Partner countries as well. As an example, ESA plans to broaden the relevant utilization rights to all European Union Member States.

Some experts believe that it would be technically feasible to adapt a U.S. rendezvous and docking system to the Chinese Shenzhou in a reasonable amount of time. The important factor is to be able to agree on common standards for safety and reliability. The technology used would be well known and need not involve sensitive technology transfers. The use of American co-pilots and American rendezvous/docking training and mission operations specialists for Shenzhou/ISS missions could provide assurance of safe and successful operations with China. Additional means of access to the ISS could improve its resilience and sustainability but all ISS partners would have to be in agreement before such a major step is taken.

The increased participation of new actors and stakeholders in human space exploration activities requires cooperative frameworks that take into account differences in political systems, budget cycles, and exploration goals, as well as culture and business practices. National and international political engagement will be necessary to aid in the development of sufficient capability to implement an innovative long-term roadmap for human space exploration that will also involve newly emerging space-faring nations in a meaningful way. Lessons learned from the International Space Station experience should be given particular attention in developing practical measures for future cooperative activities.⁵

5 *ISS Multilateral Coordination Board, "International Space Station Lessons Learned As Applied To Exploration," Kennedy Space Center, July 22, 2009*

Brief highlights for the major space-faring states are presented below.

CNSA/China: China is following a deliberate, steady pace in their human space program with a series of well-planned quantum steps. A taikonaut in 2008 performed China's first extravehicular activity (EVA). Further missions on manned spaceflight include the demonstration of rendezvous and docking technology followed by a space lab mission. Recently, China has announced that two female taikonauts have been selected. The ultimate goal of Chinese human spaceflight program at this stage is to build up to a permanent space station in the 2020 time period. In 2011, China will launch Tiangong-1, the first space lab module, followed by an unmanned Shenzhou-8 to dock with it. China has, on at least two occasions, publicly announced its desire to join the International Space Station (ISS) program. The Chinese Shenzhou spacecraft, launching atop a Long March 2F rocket, provides a possible alternate means of transportation and an additional capability (apart from Soyuz, Orion, and others) for manned access to ISS in the next decade. Currently, there is no official announcement of any Chinese manned lunar mission, but it is believed that this topic is under discussion within the space community and space scientists in China.

CSA/Canada: Canada is an active ISS partner and trains an astronaut corps. Canada has been involved in space exploration for more than 25 years with its robotics, science and astronaut corps contributions. As part of its space plan, the CSA objectives are to ensure full utilization of the ISS, to be active in on-orbit robotics servicing, to be a partner in the Mars Sample Return series of missions, to participate in human and scientific exploration of the Moon, Mars and asteroids.

ESA/Europe: ESA and Europe have provided essential contributions to the International Space Station through the Columbus orbital laboratory, the Automated Transfer Vehicle (ATV), and other ISS infrastructures (Node 2, Node 3, and Cupola). Europe's space exploration environment is also evolving as many European decision makers are realizing that it is time for Europe to take a long-term political decision on future exploration programs. The political dimensions of space exploration and its economic and strategic applications are therefore in the process of being more fully acknowledged in Europe. ESA is currently working with the European Union to establish an "EC Strategy and Associated Budget for European Exploration Activities." ESA has recently developed a long-term cooperation plan with NASA to use all launch opportunities for missions to Mars.

ISRO/India: India is embarking on new space endeavors that include space exploration and human spaceflight. The India Space Research Organization (ISRO) will contribute an orbiter - Chandrayaan-2 - and a mini-rover to the Russian mission Luna Resource/2. The combined mission will be launched with an Indian rocket. Recent technological studies on human spaceflight scenarios have led to a proposal to the Indian government

for a first manned mission in the 2016 timeframe and an ambitious program of human spaceflight to follow. The government has not yet accepted this proposal.

JAXA/Japan: In the government document “Basic Plan for Space Policy” released in June 2009, Japan intends to continue to achieve world-leading scientific results and strengthen cooperation in space science. Japan’s participation to the ISS focuses on the development and exploitation of the Japanese Experiment Module “Kibo,” along with the H-II Transfer Vehicle (HTV). Japan has decided to participate in the extension of ISS utilization until at least 2020. The Japanese Hayabusa mission explored the near-Earth asteroid Itokawa and returned to Earth in June 2010. Japan’s space organization and policy is currently under review by the new Japanese government.

KARI/South Korea: Korea is making notable investment and progress in its indigenous space capability. Korea is part of the Global Exploration Strategy, but it also plans to send several spacecraft to the Moon including a lunar lander. Korea’s first astronaut, Yi So-eon went to the ISS aboard a Russian Soyuz in April 2008. Efforts are continuing on development of a Korea Space Launch Vehicle-1 in cooperation with Russia.

NASA/U.S.: The USA has decided to continue ISS operations until 2020 and beyond, with a major emphasis on ISS utilization. The United States is presently seeking to spur development of commercial cargo and even human LEO access to space. Commercial suppliers will not eliminate the gap in U.S. human access to space after the retirement of the Space Shuttle, but they may offer a longer-term approach for LEO access for the United States and others. The technology to get astronauts to LEO has existed for nearly fifty years. The challenge is to determine whether there can be a safe, dependable, yet commercially viable approach that will allow NASA to focus more attention on human missions beyond LEO. The April 15, 2010 speech by President Obama at the Kennedy Space Center indicated that he supported development of an Orion crew exploration vehicle that would initially serve as a rescue craft on the ISS as well as a technology test bed. It may then be available for use in future missions to the Moon or asteroids. In addition, the U.S. Administration has proposed a heavy-lift vehicle capable of supporting missions to the Moon and Mars that would begin development in 2015. This would serve as a complementary system to commercial LEO efforts. The Congress passed a NASA authorization bill in September 2010 that calls for accelerating development of a heavy-lift launch vehicle, a continuation of U.S. government efforts to ensure access to Low Earth Orbit and the addition of a Shuttle mission to the International Space Station. Technical studies are underway to determine whether the heavy-lift vehicle should be based on Shuttle-derived components or those of existing Evolved Expendable Launch Vehicles (EELVs) such as the Delta IV and Atlas V. In response to media questions about destinations for U.S. human spaceflight, NASA has stated that current plans calls for a human mission to a Near Earth Object, i.e., an asteroid, although lunar science and exploration will continue to be a priority.

Roskosmos/Russia: Several years ago, the Russian government adopted a new Federal Space Program (2006-2015). The 10-year plan includes as a major goal the development and maintenance of orbital space constellations to achieve socio-economic benefits for Russia. Russia's Security Council also approved a draft space policy for the period until 2020. This policy aimed at retaining Russia's status as a leading space power. The exploitation of the Russian ISS segment and the development and replacement of its crew and cargo transportation capabilities are among other major items listed in the Federal Space Program. Russia has decided to continue ISS operations until 2020 and beyond. Following the decision of the United States to terminate shuttle operations after 2010, and the existence of a gap before the entry into operation of the next US, Chinese or commercial human spaceflight vehicle, Russia will play a crucial role in providing support to the ISS. Being the only country capable to deliver crew to the ISS elevates Russian importance in providing logistical flights to the station.

6. Priorities for Human Spaceflight and Required Infrastructures

The International Space Station is the largest, most complex, and most international engineering project ever undertaken. It has been a diplomatic and technical success and with the completion of the assembly phase, the Partners' utilization efforts will determine whether it will be a research success. The large investments in the infrastructure will bear fruit as work transitions from construction to utilization. The time is now to reap benefits by utilizing the ISS to its fullest extent, not only in the classical areas of microgravity materials science, biology, and fluid physics but also in new applications such as exploration technology test beds and climate change monitoring. The ISS should be fully exploited to study and simulate human long duration missions to Mars including the effects of the radiation and microgravity environments and isolation on human physiology and crew operation performance. The ISS is an extremely valuable existing orbital asset that serves as the foundation infrastructure for human spaceflight and thus it should be exploited as fully as possible.

The expansion of humankind's presence beyond LEO should be done in a careful, stepwise manner. The establishment of a human outpost beyond LEO is one logical next step while shorter duration missions could explore other areas of the Moon and evaluate the potential for local, man-tended facilities (e.g., astronomical observation stations on the lunar far side). The proximity of the Moon for technology development, planetary operational experience, and the investigation of intriguing lunar science questions are strong arguments for such efforts prior to attempting human landings on Mars. In addition, human missions to low gravity bodies such as asteroids and the Martian moons provide practical destinations for gaining deep space operational experience and scientific discovery prior to human landings on Mars. All of these efforts should be supported as much as possible by robotic means as both pathfinders and complementary support for human missions.

6.1 Destinations

LEO – there is a need for at least two redundant human space transportation systems to LEO on international space cooperative projects. The primary immediate need is to support the International Space Station and then other locations such as human-tended facilities in orbit with the ISS and elsewhere in Earth orbit. Orbital complexes to support exploration missions beyond LEO and new scientific and commercial activities of all types should be considered.

Moon – an outpost should be established. In addition, the capability is needed to access all areas of the Moon for scientific exploration and human-tended facilities as opportunities arise (e.g. radio astronomy and telescope facilities on the Far Side).

Asteroids – human missions to Near-Earth Objects with relatively modest delta-v requirements comparable to lunar missions can be accomplished without having to

construct complex landing systems (such as those needed to access the lunar and Martian surfaces). A variety of NEOs may be visited in coordination with a global survey effort to identify, track, and characterize the asteroid population. Priority should be given to the identification and characterization of asteroids that are potentially hazardous objects.

Mars – it is too soon to set priorities for specific sites on Mars given uncertainties about required technical capabilities. The global space community does not yet have the capability to safely launch or land equipment of the mass necessary for human missions to Mars. We also do not have enough information to efficiently balance the risks of new propulsion systems, exposure of humans to the space environment, and operations many months away from Earth. However, planetary protection requirements will be a major consideration for both robotic and human visits. For example, human missions may need to avoid areas of methane concentration until extensively surveyed by robots to avoid contamination.

6.2 Required In-Space Infrastructures

Space missions are expensive and risky. Therefore, building necessary in-space supporting infrastructure should be done at lower expenses and risk, especially for human missions where human life is at stake. To this end, an openly accessible platform in LEO is an important requirement to facilitate human space missions. Space infrastructure should be not only mechanically interoperable by international partners but should use open, interoperable standards for communications, navigation, and safety purposes. Given the long-lived nature of space infrastructures, care should be taken to minimize the creation of orbital debris and should seek to reduce existing debris wherever feasible.

The baseline crew vehicle to access ISS for the next few years is the Russian Soyuz capsule, following the Space Shuttle retirement. However, to gain access to ISS and to LEO at least two redundant human space transportation systems should be available to increase the robustness of access to the ISS.

NASA has been developing a human space transportation system, the Orion crew exploration vehicle and Ares-1 launcher, over the past four years. Orion is close to a critical design review and may be operational in three to four years for ISS crew and cargo transportation. A European crew transportation vehicle using a human rated Ariane 5 and capsule based on an evolution of Europe's ATV (i.e. the Advanced Return Vehicle, ARV) could be a potential additional system and provide redundancy to other human-rated systems. The Chinese Shenzhou spacecraft, launching atop a Long March 2F, as well as the Ukrainian-Russian Zenit launch man-rated vehicle could also provide alternate means of transportation for human access to ISS in the next decade.

Looking beyond the current ISS, a second generation ISS could be used as an assembly and re-fuelling station for exploration missions. European elements

could include modules based upon Columbus and on the ATV. Countries such as China, India and South Korea that are not part of the current ISS partnership might provide other laboratory elements and platforms. Human tended platforms, provided by governments or commercial sources, could continue to serve the science and microgravity communities after ISS retirement.

The Moon is another ideal location to build such supporting infrastructure but for somewhat different reasons. Lunar outposts and bases are useful for scientific research, technology development, and to gain operational experience with working on a planetary surface, at a relatively short distance from Earth.

Architectures for human missions to Mars should benefit from the robotic scientific missions recommended by the Mars Exploration Program Analysis Group (MEPAG) and by Mars and Planetary Science decadal surveys. Human missions may require the extension and establishment of additional communications and navigation infrastructures as well as nuclear power sources to enable human outposts.

6.3 Areas of Cooperation

Priority areas for international cooperation to support human missions to the destinations listed above and to develop required in-space infrastructure include the following:

- Extending ISS access to non-ISS Partners for research and technology development relevant to future human space exploration in exchange of alternative logistic access to the ISS.
- Space transportation capabilities providing redundant means for human and cargo access to LEO and the interoperable potential to rescue crews from other spacecraft, including the ISS.
- Reciprocal access to the ISS and Chinese Space Stations for international cooperation.
- Adoption of open, interoperable communications protocols (e.g., delay-tolerant networks) defined through the Consultative Committee on Space Data Standards.
- Adoption of standard orbit data message formats to facilitate exchange of satellite and orbital debris location information to avoid possible collisions in space.
- Continuation of international participation in space weather modeling and forecast.
- Adoption of common interface standards for rendezvous and docking mechanisms and internal life support environments.
- Environmental Control and Life Support Systems (ECLSS) and interface standards are needed as well as more universal nutrition protocols and medical standards. Seek to use existing processes for the ISS (e.g., Multilateral Medical Operations Panel, Multilateral Space Medicine Board, and Multilateral Medical Policy Board) to non-Partner participation on the ISS.
- Human precursor robotic missions to exploration destinations.

- Support and encouragement of participation by non-space-faring states in exploration while not supporting the proliferation of ballistic missile technologies.
- Encouragement of additional government provided and commercial space platforms for international scientific research.
- Consideration of cooperative mechanism to share ground support infrastructures such as launch facilities, communications, and tracking systems in support of international cooperative missions.

7. Enabling Technologies

What key enabling technologies and infrastructures should be established, and in what sequence, to explore beyond the Earth and possibly settle an intelligent presence across the solar system with both humans and robots? How might all nations, both space-faring and non-space-faring, most effectively cooperate to create space launch, in-space transportation, power, communications, navigation, and life support infrastructures that are affordable and open to all?

Human spaceflight programs have reached a crossroads with the United States' decision to retire the Space Shuttle and uncertainty about how rapidly a crew exploration vehicle and its launch vehicle and others may be developed for future crew and cargo transportation. The Russian Soyuz will soon be the only vehicle to transport crew to and from the ISS, as well as provide crew rescue capability. Though China entered human spaceflight in 2003 with the launch of Shenzhou, they are still in the early stages of gaining operational experience in areas such as EVA, rendezvous, docking, and construction activities in space. As human space exploration efforts proceed, it will be important for all space-faring nations to decide what level of human spaceflight capability and technology they require for themselves to fully participate in the Global Exploration Strategy.

Human space missions are invariably expensive and technologies to reduce mission costs are a priority. The technologies developed must ensure reliable functioning of hardware in the presence of environmental conditions such as galactic cosmic rays, solar particle events, diverse aerothermal environments, planetary dust, and increasingly, orbital debris. Many of the technologies needed for deep space human missions are not yet mature, and the experience gained on planetary robotics mission, space station and other technology development programs needs to be adapted for such missions.

7.1 Enabling Technologies List

The major enabling technologies that are to be developed/matured for deep space Human missions include:

1. Human rating of launchers/spacecraft
2. Propulsion
3. Automated rendezvous, docking and capture
4. Regenerative environmental control life support systems
5. Entry and re-entry technologies
6. Autonomous landing technology
7. Surface infrastructure/non-terrestrial mining/surface habitation
8. Robotics for in-space and planetary surface use

9. Interplanetary data and information exchange
10. Energy systems
11. Space exposure and health care at remote locations
12. Planetary protection/sterilization

7.1.1 Human Rating of Launchers/Spacecraft

The launchers and spacecraft for human missions should be “human-rated” by ensuring high reliability and providing viable crew escape mechanisms. Human rating requirements and standards should be as transparent and consistent as possible to facilitate crews from different countries flying on alternative vehicles. Whatever the final destinations for human spaceflights, the ability to reach LEO will remain indispensable. An imperative is to have several, preferably more than two, different launch systems for access to LEO. It would be expedient – in terms of saving time, financial and human resources – to give priority to human-rating launch vehicles with proven track records in launching non-human payloads while newer systems are developed. Testing and certification procedures should be consistent and applied appropriately to all vehicles, whether operated by governments or the private sector.

In setting standards for human rating of space vehicles, the internal crew volume available is also an important consideration. While not a near-term human-rating issue, it will likely be a crucial consideration for flights beyond the Moon. Ideally the crew would like to have as large a volume as possible, especially for long duration missions. The volume allocated for crew is severely constrained however by launch vehicle capacities and the need to reduce the mass of space vehicles. Constrained space induces many crew disorders such as sensory deprivation, fatigue, low morale, mental health and sleep disorders and other issues. The optimal volume per crew for missions lasting for more than six months seems to be in the range of 18-20 cubic meters. With increasing space vehicle size, there are associated issues such as additional mass, more challenging propulsion requirements, and increased cross-sections to meteorite/debris impact. There should be technology improvements to increase the volume available to crew to an optimal figure as this will provide the crew with better psychological conditions and reduce risks to crew performance.

7.1.2 Propulsion

Propulsion, both to escape the Earth’s gravitational well and reach orbit, and to travel within the solar system, is the primary requirement for space exploration. For missions beyond LEO, the distances and velocities involved require spacecraft that can support humans autonomously for months or years, without re-supply from Earth.

Chemical rocket engines using liquid and possibly solid fuel will remain, for some time, the primary propulsion devices for access to LEO. For human space missions where reliability is critical, it is best to use propulsion system with proven records. To mitigate overall mission risks, crew and cargo should be launched into LEO separately using human-rated launchers and heavy-lift rockets as necessary.

When selecting energy installations/propellants for long-duration human flights (such as flight to Mars), an important consideration is explosion safety. A comprehensive solution to this problem would be to maintain energy carriers/propellants inert in their initial state and make them active only at the time of required functioning. For example, attempts are being made to research how non-terrestrial sources of H₂O and SiO₂ may be used to extract O₂ and H₂ for use in orbital stages as well as closed cycle life support systems. These chemicals are safer to handle than other options such as hypergolic bi-propellants and offer mass and performance benefits for long-duration flights.

For future lunar missions, nuclear propulsion is likely to be too expensive and unwarranted. However, new propulsion technologies must be found or implemented to allow human exploration of interplanetary space beyond the Moon and near Earth asteroids with shorter transit times. The solar-electric propulsion (SEP) does not appear to be a viable solution for these missions, because the power and energy per unit mass is free but too low. SEP is however an attractive solution for many non-human missions, including cargo resupply from LEO to other destinations.

Nuclear propulsion is an enabling technology for future space exploration and especially for faster human interplanetary missions. The two main alternatives now conceivable in the next twenty to thirty years are Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP). The main trades-offs between NEP and NTP, besides specific impulse and thrust levels, are cost and mass. The mass factor is dominated by the size of the space thermal radiator and the low overall energy efficiency of NEP due to currently known energy conversion methods. With a sufficiently large nuclear reactor (e.g., in the range of 100s of megawatts), a human mission could reach Mars in less than three months using NEP. These findings may apply to asteroid belt missions as well. To get a feeling for numbers, a set of 100 Newton electric thrusters capable of 15,000 seconds of specific impulse requires a 15-megawatt power source; which roughly translates into the need for a 50-megawatt reactor. This is a technically feasible capability as the largest space nuclear reactor built under the U.S. NERVA program, Phoebus IIA, produced 4.2 Gigawatts. However, these power ranges still give pause to mission planners at this time.

Studies indicate spacecraft mass can be minimized by combining NEP operations with an appropriate power-on schedule during the Earth escape and trans-Mars portions of the trajectory and subsequent return. When approaching and flying-by a planet, the latter's gravitation is used while the spacecraft provides the primary propulsive power on the way between planets. Restartable, throttleable engines within the range of tens of kilo-Newtons of thrust range are also important for future exploration missions to planetary surfaces. Missions to the giant planets (e.g., Jupiter and Saturn) have been studied using probes with nuclear reactors with power in the 50-100 kilowatt range. However, because of the radiation environment and other reasons, there is little interest in human missions at this time and the technology to perform them is likely beyond the time horizon of this study.

Development of reliable ion and Hall Effect thrusters could enable future electric thrusters capable of operating in space for years. Powering high thrust, high specific impulse, ion thrusters is feasible with modern nuclear reactor systems that can also double as in-space and planetary surface power sources. Future high performance space nuclear reactors are likely to require novel nuclear fuels. One class consists of so-called metastable isotopes with power densities intermediate between those of chemical and fission power sources. These fuels do not fission, but decay, emitting photons rather than neutrons resulting in lighter and more manageable shielding.

Future nuclear fuels may enable a drastic reduction of total reactor mass, with possible added complications due to the need for in-flight refueling. High reliability mechanical power generation with redundant turbo-machinery might be replaced by solid-state conversion within the next twenty years. Electric ion thrusters capable of using the electrical power produced by nuclear reactors need to be scaled up and improved, but not invented. If erosion challenges can be solved, Hall Effect and more general Magnetoplasmadynamic (MPD) thrusters (e.g., VASIMR) may become the next step. This would enable propulsion systems with thrust in the range of 100s of Newtons and with significantly higher specific impulse than possible today. Because of its inherent lower specific impulse, NTP has lost some appeal, but dual mode Nuclear Thermal Rocket - Nuclear Electric Propulsion (NTR-NEP) in the mid-term and fission fragment engine technology in the long-term may be the way for nuclear rocket engines technology to combine high thrust with an acceptably high specific impulse.

In-orbit fueling provides an alternative means of supporting missions requiring large velocity changes. Segments of the complete spaceship can be sent into LEO through multiple launches and the final spaceship is then assembled, fueled and launched in-orbit. This approach may mitigate the need for using a large heavy-lift vehicle. While being able to transfer fuel to orbit is important, the ability to store fuel (especially cryogenics) for long duration with low or no boil-off is also crucial

if operations costs are to be minimized. Potential hazards associated with fuel storage and in-orbit fuelling may threaten the safety of a supporting space station, and this hazard should be carefully evaluated before any mission is carried out in this way to determine whether a specialized orbital facility is actually needed. Significant R&D is needed to resolve the issues associated with fuel storage and in-orbit transfer.

7.1.3 Automated Rendezvous, Docking and Capture

Deep space human missions will require a major increase in Earth orbital activity and a consequent need for efficient and reliable automated rendezvous, docking, and capture systems. Modules will be launched into Earth orbit, assembled and then launched to their final destinations. These modules may consist of housekeeping modules, docking modules; transfer vehicles and crew escape vehicles. Space stations can be used as a support base for space assembly operations. Advances in the assembly of large systems in space with less human intervention will create a demand for technologies involving precision sensors, alignment techniques and novel assembly methods.

There is a need to extend the current ISS LEO capabilities for rendezvous and docking into new areas, both in LEO and for rendezvous in lunar and Mars orbits. The latter capability is particularly relevant for robotic sample return missions as well as approaches to low gravity bodies such as asteroids. The extension of LEO capabilities towards applications such as space tugs and assembly vehicles could have application for large orbital debris remediation and servicing vehicles.

7.1.4 Regenerative Environmental Control Life Support Systems

The identification and further development of regenerative environmental control life support systems (ECLSS) technologies is a pre-requisite for human exploration beyond LEO. For long duration missions, the most viable option is to regenerate necessary material partially or fully from waste products as in Controlled Ecological Life Support System (CELSS). These systems attempt to mimic the natural process of recycling prevalent in the terrestrial environment. The challenges involved in recreating such a complex biological system include management of plants that can efficiently assimilate water, carbon dioxide, oxygen and light. Depending on the extent of recycling and regeneration, this can offer considerable saving in launch cost, mass and volumes. In addition, hazard detection systems including fire detection and suppression systems need to be further improved. For planetary surface operations, regenerative systems for both food and oxygen production are vital for long duration human missions. Such regenerative systems should minimize the amount of material released into the planet's environment and remove or kill microbial contamination that might be present.

7.1.5 Entry/Re-entry Technologies

High-speed entry/re-entry technologies for Mars and lunar return missions need to be further developed. Inflatable structures to serve as heat shields for re-entry, aero-braking, and aero-capture are also of great interest. Other technologies needed include improved thermal protection system designs and interfaces, ways of more accurately determining and modeling atmosphere densities along the aero-braking trajectory, and improved techniques for navigation and control during aero-braking maneuvers.

7.1.6 Autonomous Landing Technology

Advancements in autonomous landing technology for lunar and Mars missions are vital to the ultimate goal of landing humans on these bodies. This technology is needed not only for vehicles carrying crew but also for non-human cargo vehicles carrying supplies and fuel to outposts before and after the arrival of the crew. For lunar missions, the ability to perform autonomous soft and precision landing as well as hazard avoidance is a key enabling technology. Improvements are needed in both sensor technology, their integration within the vehicle, and the verification that the overall system will perform as expected in both nominal and emergency conditions.

7.1.7 Surface Infrastructure/ Non-terrestrial Mining/ Surface Habitation

Long duration human spaceflights necessitate the construction of habitats on other planets and building up of infrastructure for In-Situ Resource Utilization (ISRU). Enabling technologies that need to be developed include regenerative ECLSS, food production, water generation/recycling, logistics and transport for cargo and crew, and habitats. Also ISRU systems for a sustainable human exploration program to provide fuel and oxygen will be of increasing importance to minimizing operations costs. Such systems can reduce the amount of mass that needs to be brought up from Earth and thus reduce support costs.

Raw non-terrestrial materials and surface features need not be heavily modified to be useful to a human crew. Surface habitats can and must be designed to provide radiation protection. Cave or lava tubes, as well as burying habitats in local soil can provide significant radiation and thermal protection without the transport of similar shielding from Earth.

7.1.8 Robotics for In-Space and Planetary Surface Use

Modern artificial intelligence (AI) technologies have made it possible to carry out complex tasks using robotic devices. Robotic probes can be sent to increasingly remote destinations and accomplish exploration missions in harsh environments where humans could not survive. Therefore, for some exploration missions, robotic probes are a safe and cost-efficient alternative over human missions. However, because the capabilities of AI-based robots are limited by knowledge of the environment to be

explored, the use of robots in precursor missions cannot replace human intelligence and experience in dealing with unexpected events or complex in-situ experiments. Therefore, it is desirable to incorporate robotic precursor missions in the early stages of human missions as pathfinders to screen destinations and verify the functioning of critical technologies.

Eventually, the participation of human beings is vital to exploring and utilizing resources on other planets for the benefit of humanity. Robots can provide required support services and become sensory extensions and tools for human explorations thereby serving as supplements to human intelligence and physical dexterity.

7.1.9 Interplanetary Data and Information Exchange

It can take more than twenty minutes for one-way communication to reach Mars from Earth. As missions occur farther and farther from Earth, time lags and bandwidth limitations make it difficult to return large amounts of scientific data and increase the need for spacecraft to operate autonomously. As robotic and human missions in multiple locations and as the number of participating countries increases, it will be important to have common forms of interplanetary data and information exchange.

The Consultative Committee on Space Data Standards has made progress on the definition of a Delay Tolerant Networking (DTN) protocol that could support a wider space internetworking communications system, or “interplanetary internet.” Like terrestrial network backbones, an interplanetary backbone would be a set of high-capacity, high-availability links between network traffic hubs. The difference is that these network traffic hubs would in many cases be hundreds of millions of miles apart. The DTN protocol has been successfully demonstrated with NASA’s Deep Impact mission and on board the International Space Station.

7.1.10 Energy Systems

Solar energy will be a prime source of power for space missions out to the orbit of Mars. In this regard, concerted efforts are needed to increase power conversion and storage efficiencies. The development of advanced solar arrays, fuel cells and batteries are essential. These developments would also be of benefit in advanced nuclear to electric power conversion systems. Energy storage devices, such as lithium-ion battery and fuel cells, should be further improved for increasing safety, specific energy, energy density and temperature tolerance with increased reliability and life.

Future missions require advanced primary and rechargeable energy storage devices that can provide up to four to eight times mass and volume savings compared to current devices. For solar arrays to operate on planetary surfaces and on the Moon, means to mitigate the efforts of dust deposition is desired. Overall, improved figures

of merit in solar cells are needed, along with improved survivability in the expected mission environment. These improvements can be expected to have terrestrial applications as well and thus may be of commercial interest.

7.1.11 Space Exposure and Health Care at Remote Locations

Space radiation is a formidable risk to deep space human missions. The energy spectrum of the solar and galactic radiation (GCR) is wider than that emitted by any man-made onboard reactor by many orders of magnitude. Protection is still non-existent for conventional (Hohmann) trajectories and the risks of cancer are significant for spacecraft staying months in space. It must be noted that Moon and Mars habitats must also be designed with this issue in mind -- in practice requiring a shield thickness consisting of at least 1 meter of regolith during a normal solar cycle. Active protection investigated for interplanetary human spacecraft includes electromagnetic and electrostatic shielding; but both are still incapable of ensuring adequate protection. The magnetic field needed to deviate at least part of galactic particles is so high as to likely damage the crew during a conventional trip. Electrostatic shielding charges the spacecraft to an excessive extent and has similar damaging effects. Thus, at this stage, the only solution ensuring safe human space exploration must consist of much shorter travel time than assumed so far by the majority of projected or planned missions.

Technologies for radiation shielding and crew health care at remote destinations need special attention before embarking on deep space human spaceflights. Enabling technologies need to be developed to deal with various psychological aspects related to confinement in small volume for extended period of time, stress induced by being away from Earth (e.g. overview effect) and safety provisions under exigencies. This area is one that should be particular suitable for near term research using the International Space Station as a technology test bed. Enabling technologies could include special computerized schedule to increase autonomy, together with opportunities to view the Earth constantly.

Another aspect to be dealt with is the absence of Earth-like gravity in space or on other planets for humans. Absence of gravity for long duration can weaken bones, reduce muscle mass, and change the balance of crucial minerals and chemicals in the human body. Crews should be subjected to some minimum gravity-like force while on long duration missions. The situation can be different depending upon whether the mission is to the Moon or Mars or to Near Earth Objects. The effects of low gravity also negatively impact the ability of the human body to readapt to higher gravity environments like Earth, Moon or Mars after a long interplanetary flight. Compensating technologies should include simulated gravity systems in addition to biomedical countermeasures for long-duration missions.

It is quite probable that emergencies might occur in deep space missions that necessitate rescue of crew to safe destinations either on Earth or to an orbiting space station. This would require not only the rapid implementation of an emergency mission and also the prior development of technology to save crew from a damaged vehicle and their safe transfer to a rescue vehicle.

7.1.12 Planetary Protection/Sterilization

Planetary protection requirements specify protocols to minimize the probability of transporting terrestrial organisms to locations on Mars where they could jeopardize future missions to explore for life or its chemical precursors (forward contamination), and to prevent the release of putative Martian organisms from returned materials into the Earth's biosphere (backward contamination).

Committee on Space Research (COSPAR) policy and guidelines specify a scale of five different categories of planetary mission, ranging from flybys to sample return back to Earth. Increasing levels of stringency on measures taken to minimize forward and backward contamination are required as a mission is assigned to a higher category. There is currently a relatively well understood set of practices and procedures in the robotic exploration community for assuring compliance with COSPAR requirements and guidelines on planetary protection, including the use of approved materials, components, and sterilization technologies.

Although no locations beyond the Earth are currently known to meet the parametric definition of a "special region" for protection, the subsurface of Mars, as well as surface features suggesting a reasonable probability that water may be present, such as the erosion "gullies" and their associated "pasted-on terrain" will be protected as special regions until data indicate otherwise. Some of these regions are potentially of highest interest for locating landing zones and habitats in human exploration scenarios, because large persistent bodies of water or ice could be important resources for in-situ utilization as well as targets of high value for scientific exploration. At the same time, it is unlikely that humans could inhabit a Mars base for hundreds of days at a time without inadvertently leaking terrestrial micro-organisms (from space suits, habitat air locks, and the like) or becoming contaminated by Martian materials (due to inhalation of Martian dust, etc.).

Specific technologies that will be essential to permit human activities on other planets like Mars include: capabilities for cleaning and/or sterilizing hardware used to access the Martian surface and subsurface, capabilities for isolating humans from uncharacterized Martian materials, and capabilities for monitoring microbial populations throughout the mission.

7.2 New Paradigm in Interplanetary Travels

The quest to explore will continue and humans will continue their efforts to explore other planets of solar system and beyond. It is also true that deep space human spaceflight missions will be very costly, risky and last for months or years. Given these realities, the human exploratory missions have to be looked at in a different perspective. There are only a few space faring nations at present that are capable of undertaking human spaceflight missions. Other countries would like to participate in some meaningful way as they develop their own capabilities. There is therefore a need for combining the experiences and expertise of all interested space faring nations to the goals of human space exploration.

8. Potential Organization and Mechanisms for International Cooperation

Future possible organizational mechanisms for international cooperation in human space exploration should be based on the ISS “lessons learned” to date and utilize existing mechanisms such as the International Space Exploration Coordination Group (ISECG). The ISECG fosters voluntary, nonbinding international coordination that enhance information exchange concerning interests, objectives, and plans in space exploration among space agencies (see section 8.2). In addition, it should be recognized that there are many alternative mechanisms to foster information exchange and nurture international cooperation opportunities. The Committee on Space Research (COSPAR), established in 1958, promotes scientific research in space at the international level. For nearly 40 years the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) has been an important forum for discussing the development and uses of space technology. Other specialized structures exist in the area of Earth observations, such as the Group on Earth Observations (GEO). GEO is coordinating the Global Earth Observation System of Systems (GEOSS) that links current and future Earth observing systems and provides data for use worldwide.

In the domain of human spaceflight, the ISS is the most ambitious cooperative example to date and represents a major milestone that will shape future international space partnerships and exploration. The International Lunar Exploration Working Group (ILEWG), the Lunar Exploration Analysis Group (LEAG), the International Mars Exploration Working Group (IMEWG), and the Mars Exploration Program Analysis Group (MEPAG) all provide broad and experienced mechanisms for information exchange and coordination of space activities. In the past decade, these groups have addressed science questions, technology challenges, data analysis needs, roadmaps, program architectures, commercial opportunities, and public engagement aspects of robotic and human space exploration missions. A future global space exploration program should be designed to fulfill future expectations of many stakeholders, including the public, and draw on the experiences of all existing mechanisms.

8.1 ISS Lessons Learned as applied to Exploration

The ISS Multilateral Coordination Board released a summary document in July 2009 of lessons learned to date from the ISS experience. Those most relevant to human space exploration organization and mechanisms for international cooperation are shown below:

1) Carefully Balance Specificity and Flexibility in Program Agreements

Multilateral and bilateral partnership agreements need to be explicit while still allowing some flexibility for each agency to contribute to the resolution of unforeseen circumstances. The ISS Intergovernmental Agreement (IGA) and Memorandum of Understanding (MOU) documents spell out roles, duties, commitments and responsibilities for the partnership, and provide an overarching framework tested over

time with a track record of experiences for the partnership. Application to Exploration: Future international programs agreements need to be specific from the onset to deal with ownership, commitments, roles, Partner responsibilities and technical interchanges or transfers.

2) Manage Working Groups Judiciously

The ISS management framework demonstrated the utility of working groups. However, some revision remains necessary: (1) the activity of working groups must be more deeply integrated in the system to include all participants; (2) scope and authority of actions set by groups must be strictly determined; (3) number of groups should be limited; and, (4) the process of establishing and dismissing groups should be closely regulated. Application to Exploration: Exploration programs should use working groups when necessary, but not indiscriminately. The groups should consist of all participants in the subject domain, and operate under specific terms of engagement.

3) Establish Inter-Partner Technical Liaison Offices

In the ISS program, Partners agreed to establish technical liaison offices with other key Partners with whom there was major interaction. There are significant benefits in terms of easy access to program personnel and data, as well as the ability to expedite a variety of development and operational issues. Application to Exploration: Establish technical liaison offices with key Partners in order to facilitate communications.

4) Obtain Early Agreement on Common Technical Communications

The ISS international agreements provided, to the maximum extent possible, common technical communications for language, units of measurement, distributed system and element nomenclature, and interface standards (human and robotic). Application to Exploration: All exploration Partners should agree on common technical communications at the beginning of the program.

5) Use Consensus Approach to Decision Making

The practice of governance by consensus within the ISS partnership provides assurance that Partners have a voice in decisions, management and other issues. The partnership benefited from consensus building by identifying major Partners' interests, including constructive changes. A provision in which one managing Partner has the ability to make a decision in those rare cases in which consensus could not be reached is essential to ensuring that the program continues. Application to Exploration: Governance by consensus is beneficial in major international projects. Agreements should encourage consensus decisions while allowing for a means of conflict resolution in extreme cases.

6) Use a Formal Framework for International Cooperation

The ISS Program had a Governmental-level commitment from all the Partners

called the IGA (Intergovernmental Agreement). This greatly contributed toward maintaining support for the ISS program from each participating government and to the program's stability despite its complexity and long duration. Application to Exploration: A Governmental-level international commitment would be effective for exploration programs, since a withdrawal or delay of the program due to a cooperating agency's circumstances could prove critical. Even if the architecture were a "program of programs" (i.e., an integrated series of disparate programs), it would be effective to construct such an international framework for cooperation so that each participating country could view their contribution toward achieving common global goals.

7) Use a Dedicated Group to Develop the International Framework

The ISS approach of tasking a dedicated group to develop initial proposals which can be subsequently reviewed, amended and further developed in a full multilateral environment, representing all envisaged Partners, is an effective and workable approach to developing a formal framework for international cooperation. Application to Exploration: In the human exploration management process, many key parameters must be identified and assessed. Due to the increased complexity and arrival of new Partners, the decision making process needs to reach the right balance of each Partner's investments. An experienced dedicated group should be assembled for these purposes.

8) Accommodate Partner Budget Cycles

Each Partner agency in the ISS program must be aware of the evolution of policies of the other Partners, and the ways in which each Partner budgets operations. These differences are crucial in planning program milestones, in order to best build global political support. Application to Exploration: Each Partner must be aware of the budget cycles of other Partners and be willing to accommodate to the greatest degree possible. Maintaining a high level of situational awareness is beneficial in improving cooperation on both a political and a technical level, tactically and strategically.

9) Anticipate Budget Fluctuation

During the course of ISS development, each Partner's space station budget changed to varying degrees from the planned profile due to national policies. The budget strategies for each Partner's program did not always take these funding disruptions into account and was a significant factor in the delay of ISS assembly completion. Application to Exploration: Programs should take into account the probability of periodic budget discontinuities and disruptions among the Partners. Interim milestones that show technical achievements throughout the schedule are critical. A singular focus on a common major milestone that requires extensive interdependencies should be de-emphasized.

8.2 International Space Exploration Coordination Group (ISECG)

In 2007 the “Global Exploration Strategy (GES): The Framework for Coordination” was released as the first product of an international coordination process among fourteen agencies.⁶ The International Space Exploration Coordination Group (ISECG) has been created to implement and coordinate the GES. The goals of ISECG are 1) to establish a voluntary, nonbinding international coordination mechanism that enhance information exchange concerning interests, objectives, and plans in space exploration; and 2) to strengthen both individual exploration programs and the collective effort.⁷ ISECG has initiated several dedicated working groups and is developing the Global Exploration Roadmap to facilitate coordination of human space exploration activities and plans between Space Agencies. This coordination will maximize the opportunities for near-term cooperation and collaboration as well as define a common long-term vision for human space exploration. It is expected that the Global Exploration Roadmap will represent a further elaboration of the vision described in the Global Exploration Strategy (GES).⁸

8.3 Options for the Future

Human spaceflight is a challenging endeavor that spans decades and requires clear long-term goals, whether they are scientific, economic, or political or some combination of multiple interests. Inadequate funding, unstable goals and lack of international coordination all reduce the chances of mission success. Successful long-term planning and development of major space architectures for exploration can only be implemented when all stakeholders - governments, space agencies, commercial space sector, space entrepreneurs, and the public - strive for common goals at both national and international levels even as their individual motivations and priorities differ. Every nation is naturally free to choose its own “path to the stars” in light of its own national interests. For the leading space-faring countries wishing to cooperate, the Global Space Exploration Initiative gives a platform for discussion on the possible ways of interaction. A promising consensus approach envisions two steps:

Step 1: LEO missions

The present ISS mechanism is extended to non-Partner states, taking into account the ISS Lessons Learned to date. The primary focus of international cooperation for exploration should be to exploit and utilize the International Space Station.

6 (GES 2007) *The Global Exploration Strategy: The Framework for Coordination 2007* http://esamultimedia.esa.int/docs/GES_Framework_final.pdf

7 (ISECG 2008) *Annual work plan 2008 of the International Space Exploration Coordination Group*, http://esamultimedia.esa.int/docs/exploration/International-Coordination/ISECG_workplan%202008%20.pdf

8 (ISECG 2009) *Annual report 2008 of the International Space Exploration Coordination Group*, <http://esamultimedia.esa.int/docs/isecg/ISECGAR08.pdf>

Step 2: Beyond LEO missions

A closely coordinated team of space agencies using existing relationships and organizations should be set up as early as practicable to an initial set of mission architecture requirements and interfaces so as to inform technology and mission planning activities within each space agency. This is what ISECG is already carrying out with the Global Exploration Roadmap, involving fourteen countries.

Additional mechanisms may be needed, however, to coordinate political support for efforts that are broader than the ISS partnership while realistically reflecting current space capabilities. One suggestion would be to hold Heads of Agency meetings in conjunction with G-20 meetings to review major space exploration initiatives and bring this topic to the political agenda of the participating Ministers and Heads of State.

9. Sustainability

The sustainability of human spaceflight may be placed at risk by both physical, economical and political factors. On the physical side, orbital debris is a hazard to spaceflight with particular risks to human in space. International guidelines have been developed to mitigate the growth in debris, but more concerted international action may be necessary to stabilize the current debris population and reduce it over time. On the economic side, private sector investment and innovation, however modest at present, is crucial to the long-term future of human spaceflight and means for encouraging private sector participation are needed. On the political side, the countries participating in it must consider human spaceflight as an investment in the future for both national and global benefits.

Human spaceflight activities in near and medium term are being driven by recognition of broad tangible and intangible benefits. These include intangible benefits from the demonstration of continuous, highly visible international cooperation (e.g. the International Space Station) as well as encouraging young people to pursue challenging technical careers. Tangible benefits include innovations resulting from the necessity to solve complex challenges posed by the presence of humans in space. The extreme difficulty of safely carrying out human space exploration missions requires the development of many interdisciplinary technical skills, the ability to execute complex systems engineering tasks, and drives improvements in the quality of industrial supply chains. Innovations resulting from human space exploration can have many practical applications in areas such as environmental controls, medical research, and the safety of complex systems.

Creating an action plan for a sustainable exploration program over the short- and mid-term must consider the following elements:

- Define a clear and credible vision for a global space exploration program
- Provide the necessary resources
- Ensure information and open communication
- Improve cross-cultural management
- Strengthen the scientific context of space exploration
- Prioritize space programs for the benefit of humanity
- Optimize technical capacities and transnational cooperation
- Foster creativity, entrepreneurship and entrepreneurial orientation
- Provide appropriate legal frameworks for space cooperation
- Raise public awareness and invest in educational programs
- Apply strategic performance management measure

A global space exploration program is a complex system that requires stepwise implementation. Sustainability can be monitored through the achievement of technical and programmatic milestones. Defining critical success factors and corresponding key performance indicators is a prerequisite for a reasonable global space exploration strategy and will allow demonstration of the progress in achieving objectives. Similar concepts are echoed in the report on the lessons learned from ISS as applied to space exploration.⁹ These include periodic review of mission objectives to allow for a graceful evolution, aligning technical responsibilities with political and programmatic needs and national budget cycles, as well as joint public relations efforts.

Smaller “stepping stones” can be used to transcend cross-cultural barriers, leading to the development of better technical interfaces, shared legal frameworks and fostering coordination and cooperation on a broad front.¹⁰ Examples include advances in Earth-based programs, ISS exploitation, small satellite and planetary robotic missions. These efforts can address scientific and technical prerequisites and provide a foundation for the creation of successful global space exploration programs. The long-term sustainability of worldwide space exploration programs will benefit from the participation and support of a broader community outside of the current space industry, including financial and logistical support, and the inclusion of the public through a variety of measures targeted at a non-specialist audience. The involvement of existing, emerging, and developing space nations in such endeavors will both strengthen existing partnerships and foster new ones.

For all space agencies, especially those involved at the highest levels of human spaceflight, developing and maintaining systems engineering skills is a crucial need. If there are few opportunities to practice systems engineering, people cannot be expected to be proficient at it.

Under pressure to get the most out of every project and with few flight opportunities, space projects tend to become larger and fewer. One of the consequences can be a decline in developmental experience within government and industry management teams. Another consequence is less “through put” of development projects so that members of a space community spend most of their careers in a single organization or on only a few projects.

The lack of large-scale systems engineering skill is not just a concern for space programs, but also a strategic loss for a space-faring nation. It is not possible to look at the challenges facing the globe today without seeing that meeting them will require multi-disciplinary technical skills, international engagement, immense resources, and decades-long dedication. There is no more multi-disciplinary, large-scale example

9 *ISS Multilateral Coordination Board, op cit*
10 *COSPAR Panel on Exploration Report (2010) “Toward a Global Space Exploration Program: A Stepping Stone Approach” http://cosparhq.cnes.fr/PEX_Report2010_June22a.pdf*

of these characteristics than found in the space community, and human space exploration in particular. Thus, while governments should and must seek ways to tap into the commercial and international networks, they also need to sustain and grow their own internal “intellectual capital” so they can define requirements, conduct systems engineering trades, negotiate with industry as intellectual equals, and help resolve development problems that inevitably arise.

10. Public Engagement

Public interest in and support of space activities are widely acknowledged in the space community as being fundamental to sustaining long-term international space exploration programs. In the 1950s and 1960s, the “space race” brought excitement to many people. However, today space missions lack the flare of those past events and appear to have become almost routine and mundane. Public information policy surveys, marketing and advertising studies lead to similar conclusions concerning the public awareness of space activities. An important finding is that the part of society that supports the space program and believes that space exploration is a noble endeavor does not necessarily agree that governments should allocate substantial financial resources to achieve those exciting space missions.¹¹

The public is the ultimate beneficiary and supporter of human spaceflight. If space agencies are to retain the support of the public, effective means must be found to involve the public in the process and outcomes of human space exploration. Such participation may range from educational benefits to students, public education, or even opportunities for personal participation in human spaceflight as technical and economic capabilities mature.

To achieve public support for space exploration, nationally and internationally, and to channel advanced knowledge, participation and understanding into support of higher governmental spending requires a strong effort in public outreach and education activities. How can society become an integral part of a global space exploration program? What can be done to connect the public with space exploration and to reverse the perception that space exploration is an exclusive and separate remote endeavor? How can media and education methods keep up with the change in demographics of workforce, globalization, and with new communication techniques? How can we solve the paradox that public support does not correlate with the agreement to larger funding allocations for space exploration?

“Participatory exploration” is the active involvement of individuals as contributors to and collaborators in space research, science, and exploration activities. Participatory exploration embodies far more than simply exposing people to or educating them about space discoveries and exploration activities. It encourages individuals to contribute their creativity and capabilities to space exploration missions. Opportunities for participatory exploration in which advanced communications technology enables a wider range of scientists and the public to share in the human space missions. As commercial suborbital and orbital capabilities evolve, there will opportunities for direct participation in

¹¹ L. Billings, *50 Years of NASA and the Public: What NASA? What Publics?* in “NASA’s First 50 Years: An Historical Perspective,” Washington, D.C.: NASA History Office, in press and J.D Miller, *The information needs of the public concerning space exploration in a special report to the National Aeronautics and Space Administration, June 1, 1994*

space experiments by scientists and the wider public. Participatory public engagement in space exploration may be the key to improving public understanding on timescales, costs and government spending for large space endeavors and lead to long-term public support and sustainable funding.

11. Recommendations

In the past, space exploration was motivated by questions of political and military competition. What are the questions that will motivate human space exploration today and in the future? This study group report believes that human space exploration can and should be guided by questions that promote international collaboration and cooperation. To that end, motivating questions should be both simple, but profound, with implications for all of humanity. Perhaps the foremost question we can ask is whether humanity will have a future beyond the Earth? If so, what might the future be?

The ultimate objective of space exploration is to extend human presence across the Solar System and create sustainable communities beyond the Earth. Human space exploration is the only approach to achieve that ultimate objective or to even answer whether such a future is in fact possible. Through cross-disciplinary comprehensive study and exploration, humanity will be able to explore deeper into the unknown, acquire a better understanding of the universe and the Earth, and secure benefits for future generations.

Priority areas of international cooperation can be divided into several categories:

Mechanisms for International Coordination: The Global Exploration Strategy currently provides a guideline for a consensus-based approach among space agencies that allows for both independent national efforts and coordinated international cooperation. The International Space Exploration Coordination Group is currently the mechanism for developing common international space exploration architectures and roadmaps. All space-faring states agree on the need and desirability of maintaining human space activity in LEO and of extending it beyond, in coordination with human spaceflight robotic precursor missions.

Recommendation 1: Develop an integrated architecture for LEO and beyond including all human space-faring nations.

Programmatic Priorities: The first priority is to develop greater in-space operational experience through research in LEO. International Space Station Partners should increase efforts to effectively utilize the ISS for research and expand opportunities for other interested users, public and private, to conduct research on the ISS. There is a need for redundant space launch capabilities to access the ISS after the retirement of the U.S. Space Shuttle. Both government and non-government capabilities (e.g., Soyuz, Orion, and commercial) should be considered to provide more robust access to the ISS.

Recommendation 2: Define/develop a common transportation policy for LEO and beyond

Infrastructure Standards: Human space exploration will be safer and more effective if the international community adopts open, interoperable technical standards in certain key areas. Interoperable life-support systems and rendezvous and docking mechanisms should be demonstrated in LEO prior to use in deep space. Given its importance to both human and robotic missions, a first priority should be to progress the work of the Consultative Committee on Space Data Standards (CCSDS) on space internetworking and use of delay tolerant networking protocols.

Recommendation 3: Define/implement common interoperable standards for human spaceflight missions

Enabling Technologies: Heavy-lift vehicles are a crucial enabling capability for many major human spaceflight missions, in particular those to destinations beyond LEO, including Mars. However, the cost of such systems means that relatively few states will be able to provide such capabilities. Thus capabilities for in-space refueling and propellant storage and transfer would be of value to all space-faring parties. For long-duration stays on the Moon, and missions to Mars and beyond, nuclear power systems, to include both in-space propulsion and Radioisotope Thermoelectric Generators (RTGs) and surface fission reactors will be needed. For reducing the amount of mass launched from the Earth, human space missions beyond LEO will benefit from the early exploitation of in-situ resource utilization for both life support and propellant manufacture. Different countries around the world are becoming champions of varied enabling technologies required by human Spaceflight.

Recommendation 4: Define/coordinate champion countries for specific technologies amongst the human spaceflight countries

Sustainability: Orbital debris is a hazard to spaceflight with particular risks to humans in space. International guidelines have been developed to mitigate the growth in debris, but more concerted international action may be necessary to stabilize the current debris population and reduce it over time. More international cooperation between public and private sector organizations is needed to improve space situational awareness and promote codes of conduct for the safe and responsible use of space. This should include appropriate sharing of information necessary for orbital conjunction analysis using orbit data messages formats adopted by the Consultative Committee on Space Data Standards.

Recommendation 5: Define/develop an integrated Human Spaceflight Space Situational Awareness system

Public Engagement: The public is the ultimate beneficiary and supporter of human spaceflight. If space agencies are to retain the support of the public, effective means must be found to involve the public in the process and outcomes of human space

exploration. Such participation may range from educational benefits to students, public education, or even opportunities for personal participation in human spaceflight as technical and economic capabilities mature.

Recommendation 6: Define/develop an integrated public engagement plan for human spaceflight

Human Factors: The main specific element in the human spaceflight is the human presence and its associated problems. For space exploration the following factors are considered as requiring coordination: effects of microgravity, radiation dangers, psychological and interpersonal issues. A coordinated mechanism for calibrating, disseminating and exploiting data should also be implemented. This should include a coordinated effort among the space faring states to identify both synergies and gaps in their respective human factors research programs.

Recommendation 7: Coordinate research on Human Factors

Global Reach: Human spaceflight activities are carried out for the benefit of humanity and as such should concern all countries in the world. Creating global involvement for human spaceflight is an important activity affecting many global interests and thus should be brought to the attention of the United Nations Committee on the Peaceful Uses of Outer Space. Countries can participate in human spaceflight activities in many different ways depending on their national priorities and level of development. Participation can have many complementary benefits such as building national scientific, technical, and educational capacities, stimulating the interest of future generations in scientific and technical disciplines, and strengthening industrial capacities. These benefits can come from participation in both existing (e.g., the International Space Station) and future human spaceflight efforts.

Recommendation 8: Foster opportunities for as many countries as possible to participate in human spaceflight activities in view of its strategic and societal importance for humanity.

12. Conclusions

All space-faring states agree on the need and desirability of maintaining human space activity in LEO and of extending human missions to go beyond LEO (e.g., the Moon, Near Earth Objects), in coordination with robotic precursor missions. Human missions to the surface of Mars are the primary long-term exploration goal in view of the scientific interest and prospects for mankind inherent in such an achievement. Human space exploration will enable us to truly know whether humanity has a future beyond the Earth in addition to securing tangible benefits.

In the domain of human spaceflight, the ISS is the most ambitious cooperative example to date and represents a major milestone that will shape future international space partnerships and exploration. Looking forward, the Global Exploration Strategy represents a basis for a consensus-based approach among space agencies that allows for both independent national efforts and coordinated international cooperation. Current existing multinational space exploration efforts need to evolve and positively reinforce stakeholder relations to meet future challenges.

Human space exploration will be more effective and beneficial if planned and conducted with international cooperation in mind from the beginning. Such efforts represent a transition from the competitive beginnings of human spaceflight to one of routine and comprehensive cooperation. Just as Russia joining the International Space Station was a powerful symbol of the end of the Cold War, so too would the joining of China, India, and others with the ISS partners in a cooperative effort to explore the Moon, Near Earth Objects and Mars be a powerful symbol of hope for the 21st Century.

Given the strategic and societal importance of human spaceflight, the topic should be discussed at the highest political levels (e.g., during a meeting of the G-20) following preparatory discussions by the respective Heads of Agencies.

Appendix 1

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Appendix 2

References

- IAA Cosmic Study on *Next Steps in Exploring Deep Space*, Ed. Wes Huntress, Universities Press, 2007
- IAA Cosmic Study on *Dealing with the Threat to Earth from Asteroids and Comets*, Ed. Ivan Bekey, Publications ISRO Headquarters, 2009
- Harry L. Shipman, *Humans in Space: 21st Century Frontiers*, Plenum Press, 1989
- Bruno, C., (2008), *Nuclear Propulsion – An Introduction*, in: *Nuclear Space and Power Propulsion Systems*, ed by C. Bruno, Progress in Aeronautics and Astronautics Series, Vol. 225, AIAA, Reston, VA., pp. 43-90.
- Fearn, D. G., (2008), *Application of Ion Thrusters to High-Thrust, High-Specific-Impulse Nuclear Electric Missions*, in: *Nuclear Space and Power Propulsion Systems*, ed. by C. Bruno, Progress in Aeronautics and Astronautics Series, Vol. 225, AIAA, Reston, VA., Chapter 3.
- A. Degtyarev, O. Ventskovsky, E. Baranov, A. Kushnaryov, A. Berdnik, *Launch of Private Manned Spaceships Using Zenith and Mayak Launch Vehicles*. – In: Proceedings of the 1st IAA Symposium on Private Human Access to Space. – 28-30 May 2008, Arcachon, France.
- P. Ehrenfreund, N. Peter (2009) *Toward a Paradigm Shift in Managing Future Global Space Exploration Endeavors*, Space Policy 25
- Evans et al. 2008, *International Space Station Science Research: Accomplishments during the Assembly Years: An Analysis of Results from 2000-2008*
- (ISECG 2009) *Annual report 2008 of the International Space Exploration Coordination Group*, <http://esamultimedia.esa.int/docs/isecg/ISECGAR08.pdf>
- (ISS 2009) *ISS Multilateral Coordination Board International Space Station: Lessons Learned as Applied to Exploration*. Kennedy Space Center; 22 July 2009
- COSPAR Panel on exploration report (2010): *Towards a Global Space Exploration Program: A Stepping Stone Approach*
http://cosparhq.cnes.fr/PEX_report2010_june22a.pdf
- <http://mepag.jpl.nasa.gov/reports/index.html>
- <http://globalspaceexploration.org>

Appendix 3

List of Acronyms

AI:	Artificial Intelligence
ARV:	Advanced Return Vehicle
ATV:	Automated Transfer Vehicle
CCSDS:	Consultative Committee on Space Data Standards
CELSS:	Controlled Ecological Life Support System
CNSA:	China National Space Administration
COPUOS:	Committee on the Peaceful Uses of Outer Space
COSPAR:	Committee on Space Research
CSA:	Canadian Space Agency
DTN:	Delay Tolerant Networking
ECLSS:	Environmental Control and Life Support System
EELV:	Evolved Expendable Launch Vehicle
ESA:	European Space Agency
EVA:	Extra-Vehicular Activity
ELIPS:	Life and Physical Science in Space (<i>ESA program</i>)
GCR:	Galactic Cosmic Ray
GEO:	Group on Earth Observations
GEOSS:	Global Earth Observation System of Systems
GES:	Global Exploration Strategy
HTV:	H-II Transfer Vehicle
IAA:	International Academy of Astronautics
IGA:	Intergovernmental Agreement
ILEWG:	International Lunar Exploration Working Group
ISECG:	International Space Exploration Coordination Group
iMARS:	international Mars Architecture for the Return of Samples
ISRO:	Indian Space Research Organisation
ISRU:	In-Situ Resource Utilization
ISS:	International Space Station

JAXA:	Japan Aerospace Exploration Agency
KARI:	Korea Aerospace Research Institute (<i>South Korea</i>)
LEAG:	Lunar Exploration Analysis Group
LEO:	Low Earth Orbit
LER:	Lunar Exploration Roadmap
MEPAG:	Mars Exploration Program Analysis Group
MISSE:	Materials International Space Station Experiment
MPD:	Magnetoplasmadynamic
MSR:	Mars sample return
NASA:	National Aeronautics and Space Administration (<i>U.S.</i>)
NEO:	Near-Earth Object
NEP:	Nuclear Electric Propulsion
NTP:	Nuclear Thermal Propulsion
NTR:	Nuclear Thermal Rocket
RTG:	Radioisotope thermoelectric generator
SEP:	Solar-Electric Propulsion
U.S.:	United States of America

Appendix 4

Heads of Space Agencies Summit

November 17, 2010, Washington DC, USA.

This year the International Academy of Astronautics (IAA) marks its 50th Anniversary since its founding in Stockholm. In the past five decades, the Academy has brought together the world's leading experts in disciplines of astronautics on a regular basis to recognize the accomplishments of their peers, to explore and debate cutting-edge issues in space research and technology, and to provide direction and guidance in the non-military uses of space and the ongoing exploration of the solar system.

The 50th Anniversary of the IAA has been recognized and celebrated throughout the second half of the year with a series of symposia around the globe, and culminating with a Heads of Space Agencies Summit on November 17, 2010 at the Ronald Reagan Building and International Trade Center in Washington DC.

After 50 years of existence the International Academy of Astronautics is recognized by space agencies as a unique elite body that can help advancing international cooperation. It has been observed that much current cooperation programs are aging such as the International Space Station (ISS) initiated with just a few countries.

The world is flattening as many newcomers are joining the club of emerging space countries. In the meantime the major space countries face budgetary challenges and politicians as well as decision-makers face competing priorities. In addition, the USA and Russia can no longer exclusively taxi the growing international space community to low Earth orbit. The result is a need to enlarge significantly the circle of the current partners for international space cooperation.

A consensus widely recognized is that future global challenges can only be solved by international cooperation with all countries committed to work together. However space agencies have to balance new aspirations with constraints of existing programs/budgets and national interests/needs. The large number of new players brings the question: how to efficiently cooperate while the number of partners significantly increases? Confidence, trust, transparency, best practice sharing will have to be the key points for reducing impediments while promoting a

safe and responsible use of space. It is anticipated that the ISS experience will be used to leverage new cooperation.

To serve as the foundation for discussion among the Summiteers, four IAA study groups composed of renowned international experts in climate change/green systems; disaster management/natural hazards; human spaceflight and planetary robotic exploration have been assembled and have published these studies and recommendations for deliberation by agencies. This is a historic and unique event as not only 25 Heads of Space Agencies have confirmed their participation in the Summit as of October 17th, 2010, but also the IAA has thorough studies that support their discussions and provide background expert documentation.

Appendix 5

International Academy of Astronautics in Brief

Founded: 16 August 1960, Stockholm, Sweden by Theodore Von Karman. The IAA became an independent organization in 1983 and a nongovernmental organization recognized by the United Nations in 1996. President: Dr. Madhavan Nair, India, Past President: Prof. Edward C. Stone, USA, Vice-Presidents: Mr. Yannick d'Escatha, France, Prof. Hiroki Matsuo, Japan, Dr. Stanislav Konyukhov, Ukraine, Prof. Liu Jiyuan, China, Secretary General: Dr. Jean-Michel Contant, France.

Aims: Foster the development of astronautics for peaceful purposes; recognize individuals who have distinguished themselves in a related branch of science or technology; provide a program through which members may contribute to international endeavours; cooperation in the advancement of aerospace science.

Structure: Regular Meeting, Board of Trustees, four Sections: Basic Sciences, Engineering Sciences, Life Sciences and Social Sciences.

Activities: Encourage international scientific cooperation through scientific symposia and meetings and the work of specialized Study Groups and Program Committees coordinated by six Commissions: on Space Physical Sciences, D. Baker (USA), on Space Life Sciences, P. Graef (Germany), on Space Technology and System Development, J. Mankins (USA), on Space Systems, Operations and Utilization, A. Ginati (Germany), on Space Policies, Law and Economics, S. Camacho (Mexico) and on Space and Society, Culture and Education, P. Swan (USA). A major initiative of the Academy is the development of a series of "Cosmic Studies" and Position Papers dealing with the many aspects of international cooperation (see <http://iaaweb.org/content/view/229/356/>).

Events: Establishment of cooperation with national academies in UK (2008), Sweden (1985), Austria (1986, 1993), France (1988, 2001), Finland (1988), India (1990, 2007), Spain (1989), Germany (1990), Netherlands (1990, 1999), Canada (1991), U.S.A (1992, 2002), the U.S. National Academy of Engineering (1992, 2002), Israel (1994), Norway (1995), China (1996), Italy (1997), Australia (1998), Brazil (2000), the U.S. National Institute of Medicine (2002), Czech Republic (2010).

Publications: Acta Astronautica (monthly) published in English; IAA e-Newsletter; Proceedings of Symposia, Yearbook, Dictionaries and CD-ROM in 24 languages.

Members: 1243 Members and Corresponding Members in four Trustee Sections and Honorary Members in 89 countries.

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