

## PROSPECTS OF COMMERCIAL ACTIVITIES AT A LUNAR BASE

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*(Received 2 February 2001, and in final form 7 July 2001\*)*

The evolutionary stages of lunar base development are outlined, as are essential activities to be found on such bases. The primary purpose of this paper is the delineation of possible commercial activities on the Moon as well as in lunar orbit. We also choose to put these commercial activities into a larger social context. Economic issues can almost never be considered in isolation. They must be studied as one, albeit major, dimension of the human experience.

Explored will be possible and likely commercial activities at the lunar base during the period 2010-2050. We can envision the lunar economy to be partitioned into three strongly coupled sectors. One sector produces for local consumption. The second sector produces for shipment to Earth or Earth/lunar orbit, and the third sector supports the development of Mars. Of course, there is significant overlap.

Examples of commercial activities will include *in-situ resource utilization* as well as processes that benefit from low gravity and, therefore, a smaller gravity well than Earth's, hard vacuum, temperature extremes, and isolation from Earth "noise". In addition, the idea that *dual-use technologies* can be a vehicle for partially financing and supporting the development of lunar bases will be explored. By dual-use, we mean technologies that have applications in at least two different economic sectors, such as materials technology that have a military and a civilian purpose. Promising dual-use technologies for a second-generation lunar base are *self-repairing systems, low gravity and microgravity technology, micro- and nano-devices, robotic manipulators, and instrumentation*.

Finally, the related issues of the environment and territoriality will be introduced in the above context. We expect that environmental protection will be major concerns as the Moon becomes Man's second home in the solar system. In addition, the questions of ownership and of the eventual independence of colonies are sure to become issues during the period under consideration. Both of these are important issues that may, in the end, govern the pace and style of lunar and Martian economic and social development.

(This paper was originally presented at the IAA Conference in October 1999 in Amsterdam, with code number designation IAA-99-IAA.13.2.08.)

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### 1. INTRODUCTION AND OVERVIEW

Our scenario exists during the transition from the first lunar base to the second-generation lunar base. The first lunar base is generally agreed to be comprised of several space station type modules on foundations that are linked and shielded. Such a base is technically feasible in the 2010-2020 period. The first base will be on a pioneering footing, establishing a baseline for survival, including resource recovery. That being established, science and commerce will evolve. Commercial activities will be primitive and comprised of small-scale feasibility and demonstration projects. Population will be in the range of 5 to 20 people, with a broad spectrum of skills, and with tours of duty of one or two years.

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\* Editor in Charge: Koon-Meng Chua

This will lead to the second-generation lunar base that will be housed in more advanced structures, most likely designs such as hybrid stiffened-inflatable concepts. The ability to construct such structures of varying sizes will lead to differentiated structures according to function, for example, housing, agriculture, manufacturing, science, storage and maintenance. Large power generation facilities will be required, as will be broader transportation capabilities. This second-generation lunar base will expand its commercial activities beyond those of the first lunar base. There will be a possibility of approaching self-sufficiency. Essential ingredients in profitability will be the export of materials and products to Earth, and the use of the Moon as a test bed and staging area for the colonization of Mars. Population will be in the range of 100 to 300 people with more specialized skills, many of whom will be permanent residents. Here we envision the period 2020-2050, at the end of which there may be several lunar sites evolving and one site on Mars on the scale of the first lunar base.

A crucial subject related to lunar development, that is not discussed here, is *risk and reliability*. This has been discussed in depth elsewhere.<sup>1</sup>

## 2. THREE-SECTOR MODEL FOR LUNAR ECONOMY

We can delineate the lunar economy at any stage of its existence, whether pioneering or well-established, into three sectors: (i) self-sustaining operations, (ii) production for export to Earth and Earth orbit, and (iii) production for export to Mars and environs. We can anticipate that dual-use technologies will have a significant impact on the lunar economy because sectors (ii) and (iii) will be by far the largest fraction of lunar Gross National Product. The intent is that lunar economic output will in large part be for export. This is natural for a smaller outpost. Eventually, as local needs become greater, more of that economic output will be used to sustain the local population and industry.

It is expected that the first permanent lunar base will be created from cylindrical modules of the kind being used to build the space station. As such, it is expected to be in an almost exclusively survival mode. It is unlikely to be self-sustaining until well into its design life. However, it can be the site for prototype development and test beds. One of the early commercially viable activities for a lunar facility is in-situ resource recovery and utilization.

The idea of dual-use technology as a viable paradigm for the financing of a lunar base has been introduced in depth elsewhere.<sup>2</sup> A set of tables providing examples of a variety of such technologies is provided at the end of this paper. Dual-use technologies as a financial model for lunar development are briefly discussed in the next section.

When the lunar settlement evolves beyond self-sustenance, we can expect that items mined from the lunar surface, as well as those manufactured on the Moon, can be exported to Earth and low-Earth orbit. Given that it costs less to place satellites in LEO from the Moon than from Earth, we can expect this fact alone to drive certain manufacturing of such components to the lunar surface.

Once a manufacturing and mining capability exists on the Moon, it will be possible to support the settlement of Mars. In addition, future Mars explorers are likely to be trained on the Moon.

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<sup>1</sup> H. Benaroya, *Reliability of Structures for the Moon*, **Structural Safety**, 15(1994) 67-84

<sup>2</sup> H Benaroya, *Economically Viable Lunar Development and Settlement*, **J of the British Interplanetary Society**, Vol. 50, pp.323-324, 1997

H. Benaroya, *Economic and Technical Issues for Lunar Development*, **J. Aerospace Engineering**, Vol.11, No.4, October 1998, 111-118

In the following section, some activities that are envisioned as growth sectors for the lunar economy are listed and discussed. A few of these may appear far fetched today, but one has only to make a comparison of what we take for granted today (*e.g.*, GPS, cell phones, hand-held computers, massive data transfer rates) as compared to the 1960s in order to realize the difficulty one has in predicting technology only a few decades into the future.

## 2.1 POSSIBLE ECONOMICALLY VIABLE ACTIVITIES ON THE MOON AND IN LUNAR ORBIT

Some possible commercially viable activities on the lunar surface (one-sixth *g*) and in lunar orbit (micro *g*) are listed below. It is emphasized that it is currently less expensive to place an object in *low Earth orbit* from the Moon than it is from the Earth's surface. Therefore, materials that may be needed in LEO, or for other space exploration activities, such as asteroid mining or Mars development, are better supplied from the lunar surface, if possible. This fact alone justifies the use of the Moon and its orbital space as the base for expansion into the solar system. Also implied here is the need for a network of space stations in Earth and lunar orbit to manage the commercial activities between the two planetary bodies and eventually with Mars, asteroid mining activities, and the eventual colonization of the solar system.

The list that follows is not grouped according to the three sectors discussed above. There is also no differentiation between first and second-generation bases. At this stage of thinking, predictions that are too specific are unlikely to be associated with a high confidence value.

- *Remote Sensing* of Earth and the asteroids for minerals and precious materials, of Earth's environment to monitor weather, for pollution studies and land use, and by news organizations can be a valuable service. Satellites can be manufactured on the Moon and placed into LEO. The cost savings here may drive a number of industries related to satellite manufacturing to the Moon.
- *Medical Research* requiring hard vacuum and/or low gravity and/or isolation may find the lunar environment attractive. Possible examples include medical treatment of massive injuries, growth of human organs and cartilage, immune systems research, pharmaceutical research and production. There may be benefit to treating burn and trauma patients, or those with massively degenerative diseases in microgravity. The one-sixth *g* can be very helpful to those with serious injuries requiring extensive rehabilitation.
- *Materials Research* on the Moon may focus on the manufacture of single crystal components such as fan blades, engine cores, and the casting process, where improved sedimentation and cooling processes can reduce mass while increasing strength, glasses and ceramics. Production of high-end "perfect" optics is a serious possibility.
- *In-Situ and Meteor/Asteroid Materials* utilization will feed into the research and manufacturing sectors of the lunar economy. Large quantities of Helium-3 can act as a fuel for eventual nuclear fusion energy systems. Elements such as oxygen and hydrogen can be utilized to synthesize liquid rocket propellants.
- *Solar Power Generation* can be effectively a major sector of activity. The lunar surface receives as much solar power as does the Earth, without any atmospheric obstructions. A power grid can be placed strategically on the lunar surface so that 50-60% of the grid is always in the sun. Energy generated this way can more than power the needs of an early base. In addition, the surface grid can be linked to orbital transmitters for beaming to Earth.
- *Chemical Reactions and Mixing Research* can lead to unique processes that can only be produced in a low gravity, hard vacuum environment.

- *Car Body/Engine Parts* such as batteries, bearings and materials may find the lunar environment advantageous. While cars are the primary beneficiaries, all these, especially batteries, have significant space applications.
- *Board and Chip Manufacturing* that can take advantage of the hard vacuum and lower gravity are often identified as early components of a lunar manufacturing economy. This, in conjunction with the possibility of manufacturing electronics for LEO satellites, can be a major sector of the lunar economy.
- *Low and High Temperature Processes* for the manufacture of exotic materials and for in-situ materials processing will find the Moon an ideal site.
- *Hard Vacuum Processes* for the manufacture of “perfect” materials.
- *Astronomical Research* can be situated on the far side where telescopes and equipment can be effectively shielded by the Moon from Earth noise. Some astronomers believe that it may be possible to see back to the “beginning of time” from this vantage site.
- *Near Earth Asteroid Tracking* can be performed in conjunction with the astronomical research using unmanned and remotely controlled telescopes. One cannot leave asteroid events only to science fiction writers. The likelihood of a near-Earth event requires that we have enough warning to be able to deflect the missile.
- *Human Physiology and Psychology* in the space environment is certainly an important research area. No single factor in manned space exploration is more important than how humans will survive, physically and mentally, in this severe environment. *Mir* has provided us with large data sets, but more is needed before we send manned expeditions to Mars. The Moon provides us with a test bed for better understanding and for the development of coping tools.
- *Plant Biology and Growth* are critical technologies that will lead to the development of hybrid seed for Earth crops as well as food production for the lunar facility. Man in space, the Moon and Mars needs to be self-sufficient. Plants will not only provide us sustenance, but also become our air filtration backbone.
- *Entertainment and Tourism* resorts and amusement parks along with hotels and restaurants can attract huge amounts of capital. Hilton Hotels has commissioned an architectural study of a surface lunar hotel. This was not a paper study, but rather a commissioned (with *real British pounds*) study. Tourism can draw enormous amounts of capital. Space and the Moon, and eventually Mars, will certainly draw many people. The key will be to demonstrate reliable systems with very low risk.
- *Facilities for Artists* will be needed for those who would like to experiment with new vistas and environments. Artists have always been a part of the exploration of new lands. This was true when the “New World” was discovered and colonized. It can be true when “New Worlds” in the solar system are colonized.
- *Competitive Sports* will be redefined for the low and micro-gravity environment. Another huge draw of available capital is sports, both active and passive activity. It is clear that low *g* changes in profound ways the dynamic functioning of our bodies and their sports activity. Completely new sports will be developed, and known ones will be reinvented for the Moon, and later Mars.
- *Educational and Research* facilities for researchers will need to be developed for the Moon. As settlements evolve beyond the sustenance stage, we expect planetary scientists, and medical doctors, as well as a variety of researchers, to set up their labs on the Moon for their research activities. These scientists will require an infrastructure to support them and their work.

- *Operations Management* for the facilities that will be built will create many new business opportunities. In a manner like Shuttle's privatization of launch operations, it is expected that the management of the lunar base will be also done by private specialists.
- *Support Services* for the various activities on the Moon will likely be privately run. Examples include maintenance, food production, waste disposal, medical services, recycling and salvaging, security.

### 3. DUAL-USE TECHNOLOGIES AS A FINANCIAL MODEL FOR LUNAR DEVELOPMENT

The defining question is: *How do we finance projects and technological developments that are so expensive, and generally require such long time scales, that investors will not support them?* This question applies to many large-scale expensive endeavors, including lunar development. However, other than Space, such projects are viewed to be in the public interest, and, therefore, justifiably funded by government. Examples include airports, highways, environmental cleanup facilities, the military, and the Space exploration of the 1960s.

Compared to these generally closed-ended projects, with generally understood economic and social benefits, Lunar development is open-ended. This fact makes it difficult to detail its benefits because of the vastness of the enterprise. (*How would one begin to justify the multi-generation benefits of colonizing a planet over a period of one to two hundred years?*) It is also very expensive when viewed as an individual project. Attempts by proponents at justification by using cost comparisons to other national expenditures deemed less worthy, such as movie going, do not enhance public desire for funding lunar development. Therefore, it is necessary to identify segments of the larger endeavor that can be justified independently as worthy activities. Worthy is, of course, in the eyes of the beholder, so that it is advantageous to identify a variety of activities.

#### 3.1 THE NEW PARADIGM

The essential framework proposed here for supporting and managing long-term and expensive projects is to substructure the projects into smaller *independent and profitable* units. This is true regardless of the particular goal of the larger project. In the same way, the path to the Moon will be supported by scores of existing and newly created independent businesses. These businesses will be such that the whole is larger than the sum of its parts. The whole will get us to the Moon, and investors can support any or all of the parts that get us there.

While this may seem to be an obvious solution to the problem, there are many hidden difficulties in such an approach. For example, one needs to be certain that the whole project is not held together by a weak link, or a series of weak links. For robustness and reliability, a parallelism of technological capabilities is necessary. In addition, an independent entity must be created that can pull together all the pieces that we need to land on and develop the Moon. At this point, it is reasonable to stipulate that major R&D efforts in propulsion and rocketry will require major government subsidies, as discussed below. Most other efforts can be justified to investors.

One must address the question of how to coordinate such a disparate group of business enterprises and, at the appropriate time, actually embark to the Moon with its first colonists. Ideally, a leadership group must be in place to properly coordinate the design and manufacture efforts of the various organizations that are supporting lunar development. While it is not necessary to own or acquire these businesses for this paradigm to be effective, it is important that a central organization has the large picture in mind and has the

resources, intellectual and otherwise, to ensure the development of the necessary technologies to support lunar development. These resources can only be developed in a financially viable sense, meaning that we need investor interest rather than government taxation. Of course, government acts on behalf of the population and, therefore, will become a customer of any Space enterprise.

A Lunar Development Corporation (LDC) must be created that will likely be an independent company that will work towards the above goals. It will include essential professional talent, including management, science and engineering, financial, and legal teams. These teams will act as venture capitalists, coordinating activities around each venture, attracting capital for start-up endeavors that cannot be accomplished by existing industries, and attracting investors for existing companies that have a role in lunar development. All of these activities are viewed as for-profit. Part of the profits will be used to repay investors, and the remaining funds used to create the financial strength needed to initiate and support a return to the Moon. As LDC grows, it may be appropriate to include debt financing (bank) in certain instances rather than relying solely on equity financing (venture capital).

It is preferable that LDC is a for-profit corporation. An issue yet to be addressed is whether LDC is to be privately held, and therefore with no fiduciary responsibility except to its owners, or publicly held will all the requisite fiduciary duties. It may be that LDC starts out privately held and evolves into a public corporation.

It is clear from the general description that LDC must be created with start-up funds to hire the teams needed to begin planning. As part of the start-up, a business plan must identify preliminary activities that will be used to attract investors. Investors providing such start-up funds are expected to receive reasonable rates of return. Given the magnitude of the proposed venture of lunar development, a 20-year period is expected from the creation of LDC to the end of the first year of lunar colonization. It may be technically feasible to go back to the Moon in ten years if full funding is provided by the taxpayers. This is unlikely to happen. Therefore, the proposed approach, which is a bootstrapping method, is needed. Thus, the two-decade time frame.

The primary goal of LDC is to ensure that the right technologies are available when needed during the twenty-year path to lunar development. In addition, LDC will attempt to do this with dual-use technologies that are profitable for Earth applications as well as lunar needs. In this way, financing and profits can be reasonably expected. However, although our ultimate goal - the initiation of lunar development - is twenty years away, our ventures will all provide reasonable rates of return. Technologies selected for development must be prioritized according to a *critical path method* as well as an *economic benefits model* for the technology.

Once we are assured of the necessary technologies, we need to create the path to lunar development.

### 3.2 PATHS TO LUNAR DEVELOPMENT

Existing industries have a significant role in lunar development. Certainly, these industries will be the backbone of early development. However, in planning a project that will not complete its first phase of operation before about two decades, new industries are anticipated for which early stages of technical development are necessary. The technological issues for lunar development are relatively well understood. Of course, there will be debates on technical options. For example, should the prototypical lunar structure be inflatable, a truss, or within a lava tube? Nevertheless, once a choice is made, the technical issues can be addressed, even if this means that new technologies need to be developed. The long-term biomedical issues are less well understood and require continued investigation. In order for the proposed paradigm to

be successful, a significant percentage (dollar wise) of the technologies must be *dual-use*, meaning that they not only have a role in lunar development, but also have a more immediate civilian or other application. Detailed charts of potential dual-use technologies are provided at the end of this paper.

As examples, the following are promising *dual-use* technological arenas for investment:

- *Self-repairing systems* can be used to help safeguard systems that are hit by micrometeorites in Space and on the Moon. Such systems can also be utilized in monitoring and repairing micro-cracks in aircraft fuselages and other mechanical components.
- *Materials development and processing* are amongst the most economically valuable scientific and engineering activities because of the importance of new materials in our world. The same is true for technology developments for Space application.
- *Low gravity and microgravity technology* will be developing as a result of our experience with the Space station. Such capabilities, whether for fluid mechanical applications or materials processing and handling in such conditions, will become extremely important for the practicalities of spacefaring.
- *Robotic manipulators* have very broad applications. In Space and on the Moon they could be extremely useful in minimizing the workload of the astronaut construction corps. They also can be used in delicate manipulations such as medical procedures and hazardous material handling.
- *Instrumentation* is an industry with broad application. Two possible areas for investment are the monitoring of material integrity, and fluid flow control. Both have significant dual-use possibilities.
- *Micro and nano devices* are those of a size that approach the smallest of scales, even the molecular and atomic scales. Potential applications include the tiniest computers, and the strongest and lightest materials. Such devices would revolutionize manufacturing, electronics, materials, and medical procedures. The applications to the Space and terrestrial economies would be immense.

The above list is only a sample of possibilities. Once very focused and specific studies are initiated, this list would grow by orders of magnitude and it will become clear which technologies have the highest potential for dual-use and, therefore, rate of return. These technologies will form the backbone for technology development. Some of these profits will help support the less profitable, but necessary, technologies that must also be developed.

In this way, the necessary resources can be accumulated for early lunar development. *LDC will evolve as an organization that resembles a venture capital holding company, with the ultimate goal of lunar development.* Intermediate goals include appropriate technology development and the earning of profits for investors and for LDC. The long-term goal is an expedition to the Moon, to stay.

In creating the path to lunar development, various options will exist, each leading to different sequences of technology development. The path to the Moon is not unique. In fact, there may be hundreds of alternate paths that lead to the same end. However, costs will differ. Also, there is the important issue of whether a particular component should be developed in year 1 or in a more advanced form in year 15. Thus, decisions need to be made on the acceptability of certain older technologies in lunar development. What we see are hundreds of paths to the same end, but with significantly different technology and financing stops along the way. Nevertheless, at certain points in time, a commitment has to be made to use acceptable technologies so plans can be firmed and set into motion for a return to the Moon.

Also, the idea of immediate returns from advertisements at various stages of the project should not be underestimated. Much in the way of sports and Olympic endorsements, these may be viewed as positive by commercial entities.

During the last phase of this twenty-year plan, the LDC will begin to contract for the return to the Moon. Among a host of needs, LDC will contract for launch dates, bays on the Space station for systems

integration, equipment, as well as initiate training for its astronaut/settlers who have been recruited from the best of those eager to become the pioneers of the 21<sup>st</sup> century. In addition, at this stage, LDC will begin to negotiate contracts for access to facilities on the fledgling lunar base that is to be constructed. Interested parties will include government, industry and research organizations. Issues of reliability and insurance will become part of the mix. Numerous details need to be considered and engineered, from crew size and mix to the lunar base functions. Planning-beyond-twenty-years must be initiated so that the long-term vision ensures the economic viability of this lunar colony. Possible lunar-based enterprises include tourism and sports, energy production, pharmaceuticals development, medical trauma centers, materials extraction, defense, sites for R&D facilities, as well as a Spaceport between Earth and the rest of the Solar System. Science facilities will be well represented on the Moon, especially astronomical observatories.

Not all of the issues raised and discussed can be resolved *a priori*; rather, it will become clear which pose major difficulties and which will be easily handled by the evolving technologies of the next twenty years. The importance of getting started cannot be understated!

### 3.3 LAUNCH CAPABILITIES

A clear vision of reality would place launch capabilities at the head of the list of initiatives needed to place us on the Moon, this time to stay. Research and development in this area is moving briskly, primarily being driven by the booming satellite communications industry. Launch capabilities are being developed by dozens of nations. All this bodes well for the return to the Moon since the largest costs are associated with lifting mass into Earth orbit.

The trend appears to be a refinement of market segmentation, allowing satellite manufacturers to place fewer systems in orbit at one time. Currently,<sup>3</sup> Atlas and Delta rockets account for about 90% of U.S. commercial launches, each bringing about 8,000-10,000*lb* into geosynchronous orbit. An Atlas launch costs about \$80*M* and the Delta about \$60*M*. The cost is therefore in the \$6,000-\$10,000/*lb* range. Near-term (next decade) costs are expected to be cut in half. Even so, it is generally believed that costs must drop below \$1,000/*lb* for lunar development to become financially feasible.

One promising aspect to the launch problem is that nations worldwide are heavily subsidizing their national rocket development programs. Each nation that can do so recognizes that it needs to support its launch industries so as not become dependent on foreign launch technologies.

### 3.4 LUNAR RESOURCES AS A DRIVER TO LUNAR DEVELOPMENT

One line of thinking suggests that there are bountiful natural resources on the Moon that could economically justify a return to the Moon. There is abundant oxygen, about 45% of the weight of lunar rocks and soils is chemically bound oxygen, and these materials also contain considerable silicon, iron, calcium, aluminum, magnesium, and titanium, which can be extracted as a byproduct to oxygen extraction. In addition, helium, hydrogen, nitrogen, and carbon can be found in the lunar regolith.

All this suggests that many important components can be extracted, resulting in oxygen and hydrogen based rocket fuels, both for Earth-Moon operations as well as for ships going to Mars. Various metallic ores also suggest other uses.

The brightest spot of lunar resources is *Helium-3*, a light isotope of Helium and potentially a fuel for nuclear *fusion* reactors. Unfortunately, these reactors have not been engineered yet. A guess of when

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<sup>3</sup> B. Iannotta, *Rockets Take Aim at Booming Market*, **Aerospace America**, February 1998, 35-41

they may be on-line is in three decades, but that was before Congress cut off funds for the Princeton Tokamak research facility. Sad but true.

The conclusion here is that there are not enough raw materials on the Moon, even if we knew how to get there and extract them, to justify taxation to fund the creation of lunar colonies. The best approach is the paradigm shift suggested in this paper.

Mars offers even fewer economically viable rationales for would-be colonists.

### 3.5 RELATION TO MARS DEVELOPMENT

The raging battle amongst the converted is whether to include the Moon on the way to Mars. The Mars-First crowd deems the Moon to be, at best, a diversion from the real goal of colonizing Mars. The Moon-First-on-the-way-to-Mars group also supports the eventuality and dominance of a Martian civilization. However, it is clear that there are clear benefits from colonizing a planetary body three days from Earth versus one that is about a year away. From any perspective except public relations, the clear and rational way for Man into Space is via the Moon. Mars Direct ignores critical technical and physiological issues that are unresolved, pretending that existing technology need not be tested extensively before being sent on a yearlong mission to Mars with humans.

## 4. ISSUES FOR THE NEXT GENERATION

In the following subsections, we discuss several issues that directly affect the economic feasibility and activities on the Moon and Mars. These are the issues of pollution and related environmental issues, the issue of ownership, and how these affect the investor communities, including government.

### 4.1 ENVIRONMENTAL ISSUES ON THE MOON AND MARS

Human exploration and colonization of the Moon and the planets appears far off. Perhaps this then is an appropriate time to discuss issues concerning the safeguarding of the integrity of these planetary bodies. It is much easier to do this in advance of the economic development that will be explosive once it begins. Specifically, how do we, the human race, ensure that the Moon in particular, and the planets in general, survive with integrity after colonies and industrial facilities begin to be planted there during the next hundred years? We will focus on the Moon since we believe that it is the easiest planetary body upon which to begin the era of a Space faring humanity, and thus, it will be the Moon that will test our abilities to learn from the mistakes of all kinds made by civilizations on Earth.

For purposes of discussion, it is assumed that by the year 2050 there will be a well-developed human presence on the Moon. The colony, numbering many hundreds of people, will have been created as a result of a joint effort by several democratic Earth governments in partnership with a number of large and small industrial concerns. The colony is therefore governed by a group that is representative of those who financed this endeavor and created it with their engineering talents.

The purpose of the colony is twofold. One is to learn how to survive on an extra-terrestrial body that is naturally hostile to human life. Such survival depends on the abilities to be physically safe and emotionally well, to be sheltered and fed.

The second purpose of the colony is to begin to explore and use the resources of the Moon for human purposes. Such activity can result in mining and material-processing operations, synthesizing fuels from mined lunar hydrogen and oxygen, development of industries that can benefit from the one-sixth Earth

gravitational field and the hard vacuum. We have discussed these in depth above. In addition, there will be growth of less industrial activity such as entertainment, sports, and smaller-scale production.

Eventually, one can envision large lunar cities that are completely self-sufficient, that survive economically by exporting lunar minerals and finished products to Earth, and by servicing transportation, both commercial and military, between Earth and emerging settlements on Mars, its moons, as well as early mining activity on the asteroids and the moons of the gas giants of the outer solar system. However, the latter part of this scenario is quite speculative for this discussion, thus, we focus on the early lunar settlement of the year 2050.

The inhabitants of this lunar settlement will have mixed loyalties. Most were born on Earth in the early 21st century. However, some will be born on the Moon and, even if they retained a kind attitude to the planet of their parents, their physiology and psychology would be decidedly lunar. Their hearts and minds would naturally have different perspectives on how their mother planet, the Moon, as well as Mars and the outer Solar System should be developed. What may have once been viewed as property of Earth-based interests, the lunar settlements would have become entities in their own right, much like children who grow up to become individuals, unique and independent.

Therefore, that early mining operation that erased the topology of the surface as it exhumed valuable ore becomes an unacceptable form of mining to the population that now calls the Moon home. It may also become unacceptable to many on Earth as well, who are enthusiastic for our evolution beyond the confines of our planet, but are eager to protect the stark beauty of the new worlds we will visit, the new worlds we will also call home. We need to examine these issues from the perspectives of those who will colonize our solar system.

Thus, we come to the central question of how does humanity evolve into Space and the planets. How do we learn from our mistakes on Earth - ecological as well as social - so that we do not repeat them on the Moon and in the Solar System? First, we would like to list some important mistakes and then discuss how we would suggest that future generations proceed to avoid repeating them again:

- *pollution* - Our survival as individuals and as a species is directly linked to the quality of our environment. We breathe the air, drink the water, and eat food that at some point grew in the earth. It is clear that the quality of the air, water, and the earth directly affects our health. In this connection many mistakes have been made by ignoring the damage done to the environment, even after it had been well established that a degraded environment leads to less healthy humans.
- *exploitation of natural resources* - There is general agreement that economically and socially, natural resources are to be used by a local population. An essential aspect of this must be that resources need to be managed so that both current and future generations have access. A general desire exists amongst people to ensure that successive generations are not deprived or burdened for the purposes of the present. Thus, there is a general opposition to wholesale depletion of forests, farmlands, and mines. This understanding will be crucial for the Moon as well.
- *quality of the man-made environment* - Given a choice, humans prefer attractive and comfortable surroundings. However, if we look around at the surroundings in which many live, one might be led to come to the opposite conclusion. As population demands increase, the incentives are to fit many more people in smaller areas and to disregard their visual and psychological needs. Due to the stark nature of the Moon and its hostile environment, extra efforts will be required to make human habitation comfortable and enjoyable in addition to viable.

The essential principles of any new civilization must evolve from the basic democratic principles many of us cherish. In addition to the freedoms, we have seen the need for safeguarding our environment

and respecting the integrity of the planet that sustains us with air, water, whose atmosphere protects us from the harsh environment of the Solar System, and whose soil provides us sustenance. Some essential principles for the colonization and industrialization of the Moon and the Solar System are:

- Democratic principles form the basis for interactions between peoples, and in commercial aspects of the new societies.
- The integrity of the “land” must be reasonably maintained; that is, the terrain should not be destroyed in order to mine and extract material. Early in the development of the Moon, techniques must be in place for resource recovery without the devastation inherent in strip mining, even if costs rise. If society values the lunar landscape, then it must be willing to share in the economic burden of its maintenance. It is unreasonable to expect business to shoulder the complete burden.
- Because the environment is of an extreme nature, care must be taken to avoid its degradation. Any environmental repairs would be extremely difficult, costly, if they are at all possible. The Moon must be viewed as a second home for humanity, not only a big rock for mining. This is also true for Mars.
- Ownership of the Moon requires the input of the legal profession. Initially, we would expect that those who finance the colonization and development of the Moon will have certain rights. One question is whether there are national rights. For example, if the U.S. creates a colony on the Moon, what will be its rights on the Moon? One can expect that two sets of rights will evolve, one for the individual (and corporate) and the other for national bodies such as governments. Eventually, however, lunar settlements will become autonomous regions, just as did the American colonies. Hopefully, revolutionary wars can be avoided if a sufficiently long-term framework can be set up which safeguards property rights but recognizes that autonomy and eventually independence are unavoidable, as they were in the New World.

All these issues warn us that we need to understand the constraints under which we will begin to colonize and industrialize the Moon. While critics will decry the added costs associated with maintaining the environmental integrity of the Moon, we only need to look at the added costs on Earth of pollution; air and water pollution on Earth add enormous costs due to needed additional health care, lowering the quality of our food, water, air, and thus our quality and length of life. One can easily justify a careful environmental policy purely on the economic and health benefits that result, not to mention quality of life. Similarly, if one takes a long view, all will benefit by taking care of the new planets upon which we are placing settlements and proceeding to extract material.

In essence, it is necessary to affirm that only rarely do the ends justify the means. The rapid development of the Moon does not justify its physical destruction. Our goals must also be to export into space mankind's best qualities. These will be difficult issues to adjudicate.

#### 4.2 INDEPENDENCE FOR THE COLONIES

As the previous discussion alluded, it is inevitable with time that colonists on extraterrestrial bodies will eventually decide that they are descendents of Earth, not owned by Earth. In the same way that the Americas became independent of the mother countries, and properties developed by trading companies evolved into autonomous entities, cities on the Moon and Mars will demand independence from Earth. At best, a confederation may become the evolution of the link between Earth and its former colonies.

Then, given this likely path, a reasonable approach for governments and private investors to take as they prepare the groundwork for the development of these bodies is to understand the history of such paradigm shifts.

#### 4.3 IMPLICATIONS FOR INVESTORS

The bottom line for investors is that they must be as creative as they have ever been in the past. Never has the creativity of the investor community been called to a more difficult and challenging task, and never to a greater calling. The last example of such vision and courage was that of the great explorers of the 13<sup>th</sup> and 14<sup>th</sup> centuries and their benefactors. Yet, look at the result of that boldness. Today, signs of that sort of initiative are appearing. Maybe we are at the beginning of something big!

The following set of tables is based on those in the report by Hoffmann and Kaplan<sup>4</sup>.

Dual-Use Technologies: Communications/Information Systems

<b><u>Terrestrial Application</u></b>	<b><u>Technology</u></b>	<b><u>Space/Lunar/Mars Applications</u></b>
<ul style="list-style-type: none"> <li>• Communications</li> <li>• High-Definition TV Broadcast</li> <li>• Business Video Conferencing</li> </ul>	<ul style="list-style-type: none"> <li>• Ka Band or Higher</li> </ul>	<ul style="list-style-type: none"> <li>• Telepresence: Vision and Video Data</li> <li>• Interferometers: Raw Data Transmission</li> </ul>
<ul style="list-style-type: none"> <li>• Entertainment Industry</li> <li>• Commercial Aviation</li> <li>• Powerplant Operations</li> <li>• Manufacturing Operations</li> </ul>	<ul style="list-style-type: none"> <li>• Machine-Human Interface</li> </ul>	<ul style="list-style-type: none"> <li>• Control Stations</li> <li>• System Management</li> </ul>
<ul style="list-style-type: none"> <li>• Communications</li> <li>• Archiving</li> <li>• Computer Operating Systems</li> </ul>	<ul style="list-style-type: none"> <li>• Data-Compression Information Processing</li> <li>• Large-Scale Data Management Systems</li> </ul>	<ul style="list-style-type: none"> <li>• Interferometers: Raw Data Transmission Information Processing</li> <li>• System Management, Expert Data</li> <li>• Archiving/Neural Nets</li> </ul>

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<sup>4</sup> S.J. Hoffman, D.L. Kaplan, Eds. *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team*, July 1997

*Dual-Use Technologies: In-Situ Resource Utilization*

<b><u>Terrestrial Application</u></b>	<b><u>Technology</u></b>	<b><u>Space/Lunar/Mars Applications</u></b>
<ul style="list-style-type: none"> <li>• Mineral Analysis, Yield Estimation - Deep Mine Vein Location and Tracking</li> <li>• Wall and Cell Integrity</li> </ul>	<ul style="list-style-type: none"> <li>• Advanced Sensors</li> </ul>	<ul style="list-style-type: none"> <li>• Mineral Analysis, Yield Estimation of Surface Mineral Analysis, and Resource Location</li> </ul>
<ul style="list-style-type: none"> <li>• Deep Mine Robotic Operations for - Mining, Beneficiating, - Removal</li> </ul>	<ul style="list-style-type: none"> <li>• Advanced Robotic Mining</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Mine Robotic Operations for - Mining, - Beneficiating, - Removal</li> </ul>
<ul style="list-style-type: none"> <li>• Improved Automated Processing: Increased Efficiency</li> </ul>	<ul style="list-style-type: none"> <li>• Automated Processing Technology</li> </ul>	<ul style="list-style-type: none"> <li>• Remote, Low-Maintenance Processing</li> </ul>
<ul style="list-style-type: none"> <li>• Reliable, Low-Pollution Personal Transmission</li> <li>• Regenerable Energy Economies</li> <li>• Small, Decentralized Power Systems for Remote or Third World Applications</li> </ul>	<ul style="list-style-type: none"> <li>• Alternative, Regenerable Energy Economies - Methane/O<sub>2</sub>, H<sub>2</sub>/O<sub>2</sub></li> </ul>	<ul style="list-style-type: none"> <li>• ISRU-Based Engines</li> <li>• Regenerable Energies</li> <li>• High-Density Energy Storage</li> </ul>
<ul style="list-style-type: none"> <li>• Environmentally Safe Energy Production</li> </ul>	<ul style="list-style-type: none"> <li>• Space-Based Energy Generation and Transmission</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Power Generation and Beaming</li> </ul>

*Dual-Use Technologies: Surface Mobility - Suits*

<b><u>Terrestrial Application</u></b>	<b><u>Technology</u></b>	<b><u>Space/Lunar/Mars Applications</u></b>
<ul style="list-style-type: none"> <li>• Hazardous Materials Cleanup</li> <li>• Fire Fighting Protection</li> <li>• Underwater Equipment</li> <li>• Homes</li> <li>• Aircraft</li> </ul>	<ul style="list-style-type: none"> <li>• Lightweight, Superinsulated Materials</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Suits: Thermal Protection</li> <li>• Surface Facilities: Thermal Protection</li> </ul>
<ul style="list-style-type: none"> <li>• Robotic Assisted Systems</li> <li>• Orthopedic Devices for Mobility of Impaired Persons</li> <li>• Human Power Enhancement</li> </ul>	<ul style="list-style-type: none"> <li>• Robotics</li> <li>• Mobility Enhancement Devices and Manipulators</li> </ul>	<ul style="list-style-type: none"> <li>• Robotic Assisted Suit Systems</li> <li>• Human Power Enhancement</li> </ul>
<ul style="list-style-type: none"> <li>• Hazardous Materials Cleanup</li> <li>• Fire Fighting Protection</li> <li>• Underwater Equipment</li> </ul>	<ul style="list-style-type: none"> <li>• Dust Protection, Seals, Abrasive Resistant Materials</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Suits: Outer Garment</li> </ul>
<ul style="list-style-type: none"> <li>• Hazardous Materials Cleanup</li> <li>• Underwater Breathing Gear</li> </ul>	<ul style="list-style-type: none"> <li>• Lightweight Hi-Reliability Life Support</li> </ul>	<ul style="list-style-type: none"> <li>• Portable Life Support for Surface Suits</li> <li>• Backup Life Support Systems</li> </ul>
<ul style="list-style-type: none"> <li>• Remote Health Monitoring</li> </ul>	<ul style="list-style-type: none"> <li>• Portable Biomedical Sensors and Health Evaluation Systems</li> </ul>	<ul style="list-style-type: none"> <li>• Surface EVA Crew Member Health Monitoring</li> </ul>
<ul style="list-style-type: none"> <li>• Hypo-Hyper Thermal Treatments</li> <li>• Fire Fighting Protection and Underwater Equipment</li> <li>• Arctic/Antarctic Undergarments</li> </ul>	<ul style="list-style-type: none"> <li>• Small, Efficient, Portable, Cooling and Heating Systems</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Suits: Thermal Control Systems</li> <li>• Rovers: Thermal Control Systems</li> </ul>

*Dual-Use Technologies: Surface Mobility - Vehicles*

<b><u>Terrestrial Application</u></b>	<b><u>Technology</u></b>	<b><u>Space/Lunar/Mars Applications</u></b>
<ul style="list-style-type: none"> <li>• All-Terrain Vehicles for Research (Volcanoes), Oil Exploration</li> <li>• Automobiles</li> </ul>	<ul style="list-style-type: none"> <li>• Mobility</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Transportation for Humans, Science Equipment, Maintenance and Inspection</li> </ul>
<ul style="list-style-type: none"> <li>• Reactor Servicing / Hazardous Applications</li> <li>• Military</li> </ul>	<ul style="list-style-type: none"> <li>• Robotics and Vision Systems</li> </ul>	<ul style="list-style-type: none"> <li>• Teleoperated Robotic Systems</li> </ul>
<ul style="list-style-type: none"> <li>• Earth Observation, Weather, Research</li> </ul>	<ul style="list-style-type: none"> <li>• Super-Pressure Balloons (110,000 ft - Earth Equivalent)</li> </ul>	<ul style="list-style-type: none"> <li>• Mars Global Explorations</li> </ul>
<ul style="list-style-type: none"> <li>• Efficient, Long-Term Operations with Low-Maintenance</li> <li>• Machines in Arctic/Antarctic Environments</li> </ul>	<ul style="list-style-type: none"> <li>• Tribology</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Vehicles: Drive Mechanisms, Robotic Arms, Mechanisms</li> </ul>
<ul style="list-style-type: none"> <li>• Helicopters, Autos</li> </ul>	<ul style="list-style-type: none"> <li>• Variable Speed Transmissions</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Vehicle s</li> </ul>
<ul style="list-style-type: none"> <li>• Automated, Efficient Construction Equipment</li> <li>• Military</li> </ul>	<ul style="list-style-type: none"> <li>• Multipurpose Construction Vehicle Systems and Mechanisms</li> </ul>	<ul style="list-style-type: none"> <li>• Robotic Construction and Set-up Equipment</li> </ul>

*Dual-Use Technologies: Human Support*

<b><u>Terrestrial Application</u></b>	<b><u>Technology</u></b>	<b><u>Space/Lunar/Mars Applications</u></b>
<ul style="list-style-type: none"> <li>• Stored Food: US Army, NSF Polar Programs, Isolated Construction Sites</li> </ul>	<ul style="list-style-type: none"> <li>• Long-Life Food Systems with High Nutrition and Efficient Packaging</li> </ul>	<ul style="list-style-type: none"> <li>• Efficient Logistics for Planetary Bases, Long Spaceflights, Space Stations</li> </ul>
<ul style="list-style-type: none"> <li>• Improved Health Care</li> <li>• Sports Medicine - Cardiovascular Safety</li> <li>• Osteoporosis - Immune Systems</li> <li>• Isolated Confined Environments / Polar Operations</li> <li>• Noninvasive Health Assessments</li> <li>• Military</li> </ul>	<ul style="list-style-type: none"> <li>• Physiological Understanding of the Human Chronobiology</li> <li>• Understanding of Psychosocial Issues</li> <li>• Instrumentation Miniaturization</li> </ul>	<ul style="list-style-type: none"> <li>• Countermeasures for Long-Duration and / or Micro-g Space Missions</li> <li>• Health Management and Care</li> <li>• Systems / Structural Monitoring and Self-Repair</li> </ul>
<ul style="list-style-type: none"> <li>• Health Care</li> <li>• Disaster Response</li> <li>• Military</li> </ul>	<ul style="list-style-type: none"> <li>• Long-Term Blood Storage</li> </ul>	<ul style="list-style-type: none"> <li>• Health Care for Long-Duration Space Missions</li> </ul>
<ul style="list-style-type: none"> <li>• Office Buildings (“Sick Building” Syndrome)</li> <li>• Manufacturing Plants</li> <li>• Homes</li> </ul>	<ul style="list-style-type: none"> <li>• Environmental Monitoring and Management</li> </ul>	<ul style="list-style-type: none"> <li>• Environmental Control for Spacecraft Cabins, Planetary Habitats, Pressurized Rovers</li> </ul>
<ul style="list-style-type: none"> <li>• Contamination Cleanup</li> <li>• Waste Processing</li> <li>• Homes</li> </ul>	<ul style="list-style-type: none"> <li>• Waste Processing</li> <li>• Water Purification</li> </ul>	<ul style="list-style-type: none"> <li>• Closed Water Cycles for Spacecraft Cabins, Planetary Habitats, Pressurized Rovers</li> </ul>
<ul style="list-style-type: none"> <li>• Long-Life Clothes</li> <li>• Work Clothes in Hazardous Environments</li> <li>• Military</li> </ul>	<ul style="list-style-type: none"> <li>• Advanced Materials / Fabrics</li> </ul>	<ul style="list-style-type: none"> <li>• Reduced Logistics Through Long-Life, Easy-Care Clothes, etc.</li> <li>• Fire-Proof / Low-Outgassing Clothes</li> <li>• Building Material for Inflatable Structures</li> </ul>
<ul style="list-style-type: none"> <li>• Efficient Food Production</li> </ul>	<ul style="list-style-type: none"> <li>• Advanced Understanding of Food Production / Hydroponics</li> </ul>	<ul style="list-style-type: none"> <li>• Reduced Logistics Through Local Food Production for Spacecraft Cabins, Planetary Habitats</li> </ul>

*Dual-Use Technologies: Power*

<u>Terrestrial Application</u>	<u>Technology</u>	<u>Space/Lunar/Mars Applications</u>
<ul style="list-style-type: none"> <li>Batteries for: - Autos, - Remote Operations for DOD, NSF Polar Programs</li> </ul>	<ul style="list-style-type: none"> <li>High-Density Energy Storage</li> <li>Alternate Energy Storage (Flywheels)</li> </ul>	<ul style="list-style-type: none"> <li>Reduced Logistics for Planetary Bases</li> <li>High Reliability, Low-Maintenance Power Systems</li> <li>Spaceship Power Storage</li> </ul>
<ul style="list-style-type: none"> <li>Clean Energy From Space</li> </ul>	<ul style="list-style-type: none"> <li>Beamed Power Transmission</li> </ul>	<ul style="list-style-type: none"> <li>Orbital Power to Surface Base</li> <li>Surface Power Transmission to Remote Assets</li> </ul>
<ul style="list-style-type: none"> <li>Remote Operations for: - DOD, NSF Polar Programs</li> </ul>	<ul style="list-style-type: none"> <li>Small Nuclear Power Systems</li> </ul>	<ul style="list-style-type: none"> <li>Surface Base Power</li> <li>Pressurized Surface Rover</li> <li>Interplanetary Transfer Vehicle</li> </ul>
<ul style="list-style-type: none"> <li>Remote Operations for: - DOD, NSF Polar Programs</li> <li>High Efficiency Auto Engines</li> </ul>	<ul style="list-style-type: none"> <li>High Efficiency, High Reliability, Low-Maintenance Heat-to-Electric Conversion Engines</li> </ul>	<ul style="list-style-type: none"> <li>Energy Conversion for Planetary Bases: - Low Servicing Hours, - Little or No Logistics</li> </ul>

*Dual-Use Technologies: Structures and Materials*

<u>Terrestrial Application</u>	<u>Technology</u>	<u>Space/Lunar/Mars Applications</u>
<ul style="list-style-type: none"> <li>Vehicles</li> <li>Fuel-Efficient Aircraft</li> <li>Modular Construction, Homes</li> </ul>	<ul style="list-style-type: none"> <li>Composite Materials: - Hard, - Soft</li> <li>Advanced Alloys, High-Temperature</li> </ul>	<ul style="list-style-type: none"> <li>Cryogenic Tanks</li> <li>Habitat Enclosures</li> <li>Pressurized Rover Enclosures</li> <li>Space Transit Vehicle Structures</li> </ul>
<ul style="list-style-type: none"> <li>Aircraft Fuel Tanks</li> <li>Home Insulation</li> </ul>	<ul style="list-style-type: none"> <li>Superinsulation</li> <li>Coatings</li> </ul>	<ul style="list-style-type: none"> <li>Cryogenic Tanks</li> <li>Habitable Volumes</li> </ul>
<ul style="list-style-type: none"> <li>Large Structures, High-Rise Buildings, Bridges</li> <li>Commercial Aircraft: - Improved Safety, - Lower Maintenance</li> </ul>	<ul style="list-style-type: none"> <li>Smart Structures</li> <li>Imbedded Sensors / Actuators</li> </ul>	<ul style="list-style-type: none"> <li>Space Transit Vehicle Structures</li> <li>Planetary Habitat Enclosures</li> <li>Surface Power Systems</li> <li>Rover Suspensions</li> </ul>

*Dual-Use Technologies: Science and Science Equipment*

<u>Terrestrial Application</u>	<u>Technology</u>	<u>Space/Lunar/Mars Applications</u>
<ul style="list-style-type: none"> <li>• Energy Resource Exploration</li> <li>• Environmental Monitoring, Policing</li> </ul>	<ul style="list-style-type: none"> <li>• Spectroscopy: - Gamma Ray, - Laser, - Other</li> </ul>	<ul style="list-style-type: none"> <li>• Geo-Chem Mapping</li> <li>• Resource Yield Estimating</li> <li>• Planetary Mining Operation Planning</li> </ul>
<ul style="list-style-type: none"> <li>• Undersea Exploration</li> <li>• Hazardous Environment Assessments and Remediation</li> </ul>	<ul style="list-style-type: none"> <li>• Telescience</li> </ul>	<ul style="list-style-type: none"> <li>• Remote Planetary Exploration</li> </ul>
<ul style="list-style-type: none"> <li>• Environmental Monitoring</li> <li>• Medicine</li> </ul>	<ul style="list-style-type: none"> <li>• Image Processing: - Compression Technique, - Storage, - Transmission, - Image Enhancements</li> </ul>	<ul style="list-style-type: none"> <li>• Communication of Science Data</li> <li>• Correlation of Interferometer Data</li> </ul>
<ul style="list-style-type: none"> <li>• Improved Health Care</li> <li>• Sports Medicine - Cardiovascular</li> <li>• Osteoporosis - Immune Systems</li> <li>• Isolated Confined Environments / Polar Operations</li> <li>• Noninvasive Health Assessments</li> </ul>	<ul style="list-style-type: none"> <li>• Physiological Understanding of Humans</li> <li>• Instrumentation Miniaturization</li> </ul>	<ul style="list-style-type: none"> <li>• Countermeasures for Long-Duration and / or Micro-g Space Missions</li> <li>• Health Management and Care</li> </ul>

*Dual-Use Technologies: Operations and Maintenance*

<u>Terrestrial Application</u>	<u>Technology</u>	<u>Space/Lunar/Mars Applications</u>
<ul style="list-style-type: none"> <li>• Military</li> <li>• Systems and Structures Health Monitoring</li> <li>• Inventory Management</li> </ul>	<ul style="list-style-type: none"> <li>• Task Partitioning</li> <li>• Reliability &amp; Quality Assurance in Long-Term, Hazardous Environments</li> <li>• System Health Management and Failure Prevention Through AI and Expert Systems, Neural Nets</li> </ul>	<ul style="list-style-type: none"> <li>• Systems and Structures Health Monitoring</li> <li>• Inventory Management</li> <li>• Self-Repairing Technologies</li> <li>• Logistics Improvement</li> </ul>