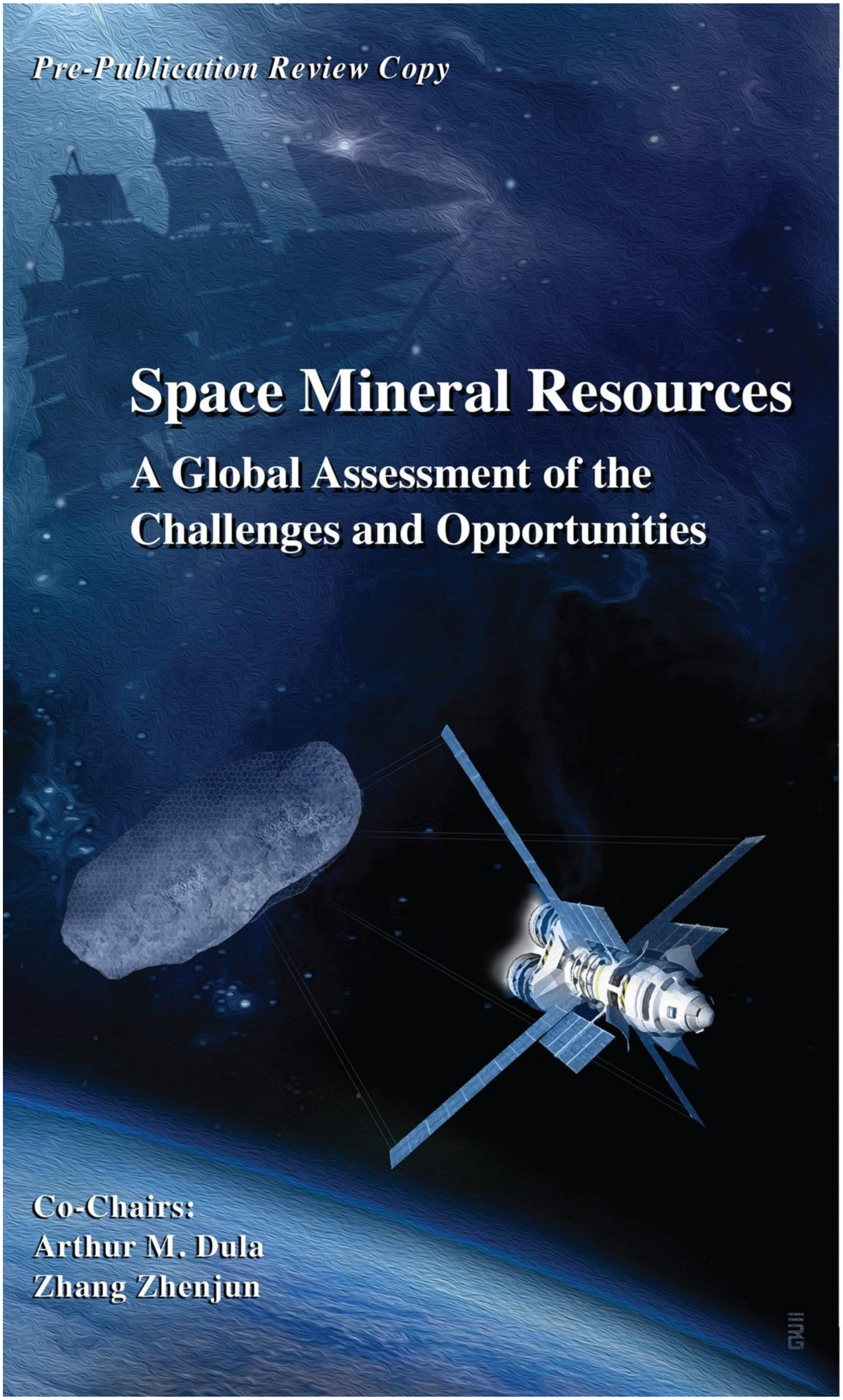

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Space Mineral Resources

A Global Assessment of the Challenges and Opportunities

Co-Chairs:
Arthur M. Dula
Zhang Zhenjun

International Academy of Astronautics

Space Mineral Resources – A Global Assessment of the Challenges and Opportunities

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The study could not have been completed to this level of detail without the timely and invaluable efforts of a diverse collection of experts from around the world who contributed not only their time and knowledge, but also provided material as well as their technical expertise for the study. These experts included the members of the study group, the chapter authors to whom significant recognition should go, and especially the editors of the study (all names are provided in Appendix A). The diverse contributors included individuals (as well as former staff now retired) from space agencies, commercial firms, universities and non-profit organizations.

Thanks are also due to the members of the International Academy of Astronautics review committees who provided highly useful comments on the final draft of this study report. In addition, thanks to Dr. Giuseppe Reibaldi for supporting the study from inside the Academy and to Dr. Jean-Michel Contant for ensuring that the study results were presented during the 2014 Head of Space Agencies Summit. Special thanks to the study research staff: Mr. Brad Blair [technical content], Jason Juren [legal content], and Anat Friedman [Secretariat].

~ *The Editors*

Note: This cosmic study has been approved by the Board of Trustees of the International Academy of Astronautics (IAA). Any opinions, findings, conclusions, or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the sponsoring or funding organizations. The Editors are aware that there is some small duplication of text between chapters, but it was felt that since the document would probably not be read from cover-to-cover, then it would be useful to have each chapter being self-sufficient so far as possible. The Editors also acknowledge that there are some differences in writing styles between chapters. This is inevitable with so many authors from all over the world collaborating on the issues. It was felt that we should leave text in the authors' own words as much as possible.

The International Academy of Astronautics (IAA), a nongovernmental organization recognized by the United Nations, was founded in 1960. The purposes of the IAA are to foster the development of astronautics for peaceful purposes, to recognize individuals who have distinguished themselves in areas related to astronautics, and to provide a program through which the membership can contribute to international endeavors and cooperation in the advancement of aerospace activities. For more information about the International Academy of Astronautics, visit the IAA home page at www.iaaweb.org.

Cover art by Eric R. Gignac

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Executive Summary

The exploitation of space mineral resources is becoming a commercial space endeavor for the benefit of humanity and profit. In 2012, the IAA approved a broad study of the technology, economics, legal and policy aspects of identifying, obtaining, and using these resources. In 2013 and 2014, multiple commercial ventures announced their intentions to initiate human (and robotic) missions to the Moon, Mars and asteroids. The question on the table is not *how* to leverage space minerals resources, but *how best* to leverage them. The purpose of this study is to provide, in one document, the current state of the art of the technology, economics, law and policy related to Space Mineral Resource (SMR) opportunities. The study will make specific recommendations for moving forward and provide a brief analysis of opportunities.

The industrial use of SMR is no longer science fiction; and, feasibility is no longer a function entirely of engineering – economics being the game changer. Preliminary economic conclusions include 1). architectures based upon returning precious metals to terrestrial markets alone appears to be a non-starter, 2). the existence of in-space customers for propellants, consumables, structural materials, and shielding could make asteroid mining economically feasible, and 3). longer-term hybrid architectures with both terrestrial and in-space customers could become feasible as costs drop and market size increases.

This study was conducted under the assumption that the international space community can make a difference. We, as an industry and as a portion of humanity, can change the current arrow of history so that it points in optimistic directions allowing the human condition to improve and expand. The change that is mandated to accomplish this is to:

Leverage the phenomenal resources available in our solar system. From space – For Space!

The study was primarily conducted by knowledgeable professionals from two industries: the space arena and the commercial mining industry. As such, this report was written for two audiences: global space leadership and the mining industry.

Major Conclusion: Members of the study group found that mining space mineral resources will enable economic travel between the Earth's surface and near-by locations within our solar system. The process of mining water from asteroids, the Moon or Mars will ensure that key elements are available at the spaceports of the future. Water will ensure that human exploration will expand beyond low Earth orbit with the profit motive driving the exploitation of resources. With this conclusion, the following is supported.

Principle Finding: SMR ventures cannot wait for government programs to lower technological and programmatic risks. Commercial ventures must determine the optimum path for commercial success and aggressively lead the way beyond low Earth orbit (LEO). During the first half of the 21st century, space leadership will come from commercial enterprises and not depend upon government space programs. One concept that would leverage this series of initiatives is to convince government agencies that commercial enterprises will be there first and will be able to support government explorations by selling products to them at designated locations.

Finding 1 – Technological risk reduction and engineering design: The mining of asteroids and lunar regolith is within the current state of the technical art. The extrapolation of Earth-based mining seems to be a one-for-one trade with some significant alterations due to vacuum, low gravity and temperature extremes. Many proposed solutions have been suggested and tested [on Earth] leading to positive conclusions on this topic.

Finding 2 – Legal Regime: Although space is inherently multi-national and international in its scope, experience indicates that national laws are the only framework that individual actors, both private and governmental, will accept as a means for specifically developing and acting in space. Mining and ownership of space mineral resources is parallel to national laws and, as such, is consistent within current international law. International space law has established that national laws govern national activities in outer space within the current framework. History has repeatedly demonstrated that areas controlled primarily by national, as opposed to international, law prosper most readily.

Finding 3 – Low Cost Access to Space Will Enhance SMR: Although space is inherently multi-national and international in its scope, the financial aspects of any activity focuses upon the initial lift to orbit costs. At the present time, access to space is exorbitant and can only be justified as necessary, as there are no alternatives. The finding is that:

> Low cost access to space will ENABLE space mineral resource activities ensuring that the commercial imperative is supported. Reducing cost of delivery to an EML-1 Lagrangian spaceport by two orders of magnitude will ensure that commercial entrepreneurs will spring up and pursue the vast opportunities then available.

Finding 4 –Timely Study Completion: The conclusion of this Academy study during the spring of 2015 is timely. The results of the 30-month activity have stimulated interest across the spectrum of space professionals in parallel with three ground breaking workshops. These occurred before completion of this document with another session added to the yearly IAF Congress – "Space Mineral Resources, Asteroid Mining and Lunar/Mars In-situ," 12-16 October 2015 in Jerusalem.

A – "The Economics of NEOs:" This workshop at NASA Ames Research center was conducted on 6-7 September 2014 with the aim: "… to serve as a catalyst for discussions and to foster collaborations between industry, academia and government." The summary of the workshop was released to the IAA and is presented in Appendix H.

B – "Space Mineral Resources Governance:" This meeting was held in the Hague on December 1, 2014. The key result from this activity was the formation of a "Hague Space Policy Working Group."

C – "Towards the Use of Space Resources:" This follow-on meeting of the Ames workshop was conducted on 20-21 March 2015, in Luxembourg with the principal focus of understanding the relationship and needs of the commercial ventures and parallel government activities. The workshop was sponsored by the Minister of Economics of the Luxembourg government. Much discussion occurred around risk identification and investment vs. technological readiness level knowledge.

The key feature of Finding #4 is that commercial space ventures are currently aggressively investing in risk reduction and reaching out to form commercial and governmental partnerships. These types of actions, in the past, have led to development of major new industries. This will probably be no different!

Basic Roadmap

During the study, multiple commercial SMR corporations submitted roadmaps towards profitable mining operations in space. The basic approach seems achievable:

Phase One:	**Initiate the business infrastructure on Earth 2014-2020**
Phase Two:	**Execute prototype flights to potential asteroids as well as testing hardware in LEO 2015-2022**
Phase Three:	**Initiate mining operations with sale of product 2018-2029**

Expected Results: Selling water at the Earth-Moon Lagrangian Point #1.

Establishing spaceports and selling water that was mined from the Moon or asteroids will enable growth into our solar system. This growth will be remarkable because the essential elements come from lunar or asteroid water sources at a much cheaper price than lifting it from the surface of the Earth. When one realizes that fuel is over 80% of the mass at an Earth surface launch site when trying to reach Lunar orbit, one recognizes that the price for a payload [of water?] in orbit is exorbitant. The economics show that the price to develop water sources on the Moon or asteroids is two orders of magnitude below the delivery price from Earth. A commercial venture of selling Lunar or asteroid sourced water should be successful. During the history of mankind's exploration, many early commercial ventures succeeded by finding local resources that they could sell to explorers and settlers. In the Earth-Moon economic sphere, that resource is water. The concept that has developed is simple:

Water is the Currency of Space!

Chapter One: Introduction

When I awoke this morning,
I looked around and saw nature in crisis.

1.0 Introduction:

We recycle milk containers, gasoline is $4 per gallon, water is rationed, the weather seems to be getting more extreme with more life threatening storms, asteroids are exploding over cities, and almost everywhere I go it is crowded. If I expand this perception from my small community to the global population, predictions from the Club of Rome [Meadows, 1972] seem real. Opening the resources of space will not only change our lives, it will change our destiny. The question is not what I can do about it; but, rather what can we all do about the multitude of problems that seem to be overwhelming our world. The answers seem simple:

- Change the equation of dwindling resources.
- Change the assumptions.
- Increase resources and produce innovations, jobs and wealth along the way

This study was conducted under the assumption that the international space community can make a difference. We, as an industry and as a portion of humanity, can change the current arrow of history so that it points in optimistic directions allowing the human condition to improve and expand. The change that is mandated to accomplish this is to:

Leverage the phenomenal resources
available in our solar system.
From Space – For Space

1.1 The NEED!

Humanity dangles perilously on the edge of disaster as indecision and apathy erode the ground beneath our feet. At our backs is a crowded and constrained world and before us is the precipice of the unknown pregnant with possibility and peril. Do we heed the cautions of Icarus' fate and plant our feet firmly in the now; or, is humanity ready to kiss the sky and carry forth the emissaries of biology, creativity and digital memory into the wild unknown? Our choice, as H.G. Wells put it, is "the universe or nothing."

The Earth may be approaching a tipping point. According to new research, projections of catastrophe predicted by the Club of Rome match current data indicating a high likelihood of environmental collapse by 2050, should current trends remain unchanged. Without game-changing events, or breakthrough technologies, humanity will be forced to confront its "limits to growth." It is clear that the world is running out of minerals and energy. Minerals are, by definition, a non-renewable resource. Humanity's consumption continues to increase as global poverty is replaced by an emerging global middle class – people who desire to live a materially affluent lifestyle. We are steadily consuming Earth's finite endowments. While new technology offers hope by creating alternatives and increasing efficiencies, the data clearly show that annual global per-capita consumption patterns continue to increase. As one author puts it, we have started down a one-way path by consuming the "last hours of ancient sunlight" [Hartmann, 1999] – a metaphor for the use of our non-renewable and rapidly depleting hydrocarbon inventory as the basis of our energy pyramid. This is an irreversible path that could easily lead to societal collapse. However, one approach is to leverage space resources and defeat that projection, as so nicely described by Dr. O'Neil [O'Neill, 1976]:

> "The fatalism of the limits-to-growth alternative is reasonable only if one ignores all the resources beyond our atmosphere, resources thousands of times greater than we could ever obtain from our beleaguered Earth. As expressed very beautifully in the language of House Concurrent Resolution 451, 'This tiny Earth is

> not humanity's prison, is not a closed and dwindling resource, but is in fact only part of a vast system rich in opportunities...'"

Figure 1-1, A Look at the Fragile Earth as a Spaceship [NASA image]

1.1.1 The SPACE OPTION: The creators of the term “Space Option,” Dr. Marco Bernasconi and Arthur Woods, believe that utilization of the space arena opens up the human condition to defeat the Club of Rome’s prediction. They believe that:

> “The Space Option concept is an evolutionary plan to meet the basic and anticipated needs of humanity through the utilization of near Earth resources - especially that of energy from space.” [Woods]

This has been discussed for years as leverage for humanity to grow gracefully into the future. The theory is that the universe is now open to space travelers. Those who venture outward to accomplish huge undertakings and make the future one of a robust world. The concept is simple. Investing in technologies, human spirit, and commercial activities to venture beyond low Earth orbit will enable humanity to keep growing positively.

On their website, Woods and Bernasconi state:

> “ Unlimited and environmentally clean energy from space would not only maintain and stimulate the global economy, the eventual exploitation of other extraterrestrial resources would guarantee future generations a sufficient supply of material resources. Thus, The Space Option provides hope for less fortunate societies on our planet to aspire to reaching a living standard substantially beyond their present situation while the present advanced societies can maintain their standard of living and continue their development - an approach to the future that differs greatly from many of the current scenarios for "sustainable development" that are under discussion. As such, The Space Option could, and should, become the primary motivation for continued space exploration and development - perhaps even becoming a more powerful driver for space activities than national prestige, security and scientific exploration have been. Indeed it should be a catalyst for the opening of a “New Space Economy” attracting the energies and capital of a new generation of explorers and entrepreneurs. If implemented in time and with sufficient commitment, the ultimate reward will be a prosperous and dynamic planetary civilization living in a healthy environment and the creation of an infrastructure in space upon which the expansion of the human species throughout the solar system and beyond could be realistically anticipated.” [Woods]

The ability to fulfill the Space Option will lead to:

- Rapid technological growth to be leveraged by space faring companies and nations as well as stimulating technological leaps in efficient manufacturing and recycling on-planet.

- Remarkable leveraging of space mineral resources for growth off-planet; and, as necessary, bring back rare resources for, consumption on Earth.
- Experiences in asteroid rendezvous and mining will result in a tremendous capability to design, track and/or divert threatening space objects.
- A phenomenal reduction in the need for coal fired energy production plants because solar power satellites will provide almost no-greenhouse gas emitting energy.
- A recharging of Earth's learning environment will be stimulated because of the vast demands for higher education/training to enter or support these off-planet roles.
- A recharging of Earth's economy will result from the vast investments and resources needed to support off-planet activities. New businesses must be creative and aggressive ensuring they are able to support these highly complex activities, both on and off planet.
- Re-energizing the human spirit as the understanding emerges that humanity has a future off-planet.
- Re-kindle the concept of Manifest Destiny: "Go up young person."

1.2 Space Mineral Resources (SMR) Concept:

This concept is a key component of the overall Space Option. Commercial space mineral resources have been discussed for decades. Krafft Ehricke, in the 1960's, emphasized the "Extraterrestrial Imperative." "This idea refers to Ehricke's belief that it was the responsibility of humanity to explore space and exploit the resources of the Solar System, in order to sustain the development of the species. There are no external 'limits to growth'" [Wikipedia, Ehricke] Now, with the profit motive as a major part of space mineral resources, the bold, creative and adventurous can lead humanity off-planet AND IMPROVE the human condition on-planet. Mining space resources offers two ways out. Technology developed for space could directly mitigate terrestrial pressures by offering new consumption alternatives, higher material efficiency, and more efficient recycling. In addition, mankind now has the ability to expand into space while creating and expanding into new biological environments to suit conditions and opportunities. There is no need to interrupt the transition of the global poor to modern standards of living given the amount of nearby space mineral and energy resources. Indeed, Dr. John Lewis estimates the population capacity of the inner solar system to be 10 quadrillion human beings at today's standard of living (1997 North American per capita consumption of minerals and energy). [Lewis, 1997]

This study will be addressing the significant need for space mineral resources as a portion of the space option approach. The essence of SMR is two-fold:

- Enhance the human condition on Earth
    - Provide Jobs
    - Re-invigorate education in science, technology, engineering, and mathematics [STEM]
    - Stimulate innovation
    - Provide a vision of return on investment [ROI] from space
    - Stimulate commercial investors for space activities
    - Provide avenues for commercial expansion into our solar system

- Initiate Commercial Movement into the Solar System
    - Provide a vision for movement off-planet
    - Provide profit motive for movement into space
    - Provide commercial products to national space exploration programs
    - Enable space exploration
    - Enable space colonization
    - Enable space based solar power satellites for Earth

These needs are being focused as the resources are dwindling on Earth. The human spirit is being challenged with clean water restrictions, clean energy limitations, job availability, and global crises of all types. Moving out into the solar system can improve the human condition on Earth through enhancement of vision and opportunities for jobs.

We have, within our collective reach, the technological, economic, legal and policy means to not only harvest this bounty but to keep us safe from the dangers of space as well. Our species now possesses the technological acumen to transform the threat of asteroid impacts into a greater material abundance than anyone conceived. The estimated population capacity of the inner solar system is ten quadrillion humans. Today's economy will scale with that growth, enabling private and commercial enterprises to thrive. To quote space pioneer Konstantin Tsiolkovsky, [Tsiolkovsky, 1895]

> "To set foot on the soil of the asteroids, to lift by hand a rock from the Moon, to observe Mars from a distance of several tens of kilometers, to land on its satellite or even on its surface, what can be more fantastic? From the moment of using rocket devices a new great era will begin in astronomy: the epoch of the more intensive study of the firmament."

Before discussing space mineral resources in general, it may be helpful to briefly examine one specific case, i.e. asteroids, in order to get some awareness of the quantities of asteroids and value of space mineral resources. There are many millions of asteroids in orbit around the sun. They range in size from less than a meter to more than 400 kilometers in diameter. They are ore bodies the size of rocks or mountains orbiting the sun in deep space. We have visited a few of them and taken photos.

This journey towards SMR exploitation will lift our societies out of poverty and create the greatest period of material and economic abundance ever imagined. It will free the world from sources of poison by moving heavy industry and dangerous research into a safer place – space. It will enable us to expand our imaginations by settling new frontiers and new worlds. It will challenge us, draw upon our courage, and free us from our terrestrial moorings. We have but to reach forward and grasp the vast energy and mineral resources of space to achieve these goals. Creative use of these resources will enable large-scale structures imagined by science-fiction, new types of habitation, entertainment, society and ecology. There is no shortage of technology, transportation systems, engineering talent, or support infrastructure to enable this future. Terrestrial industry is already equipped to process the fruits of space, and our society will seamlessly integrate the introduction of this abundance to reach new heights of prosperity. To reach the space frontier, humanity need only walk through an open door. The only ingredients left to add are capital, vision and follow-through. Dr. Stephen Hawking, taking his first zero-g flight at the age of 71, put this in one sentence: "our only chance of long-term survival is not to remain lurking on planet Earth, but to spread out into space." [Hawking, 2011] Clearly, expansion of human civilization into the universe is not a matter of whether but rather of when, how, and by whom.

Indeed, the Space Option leads to a timely opportunity to do NO Less than Save our Planet.

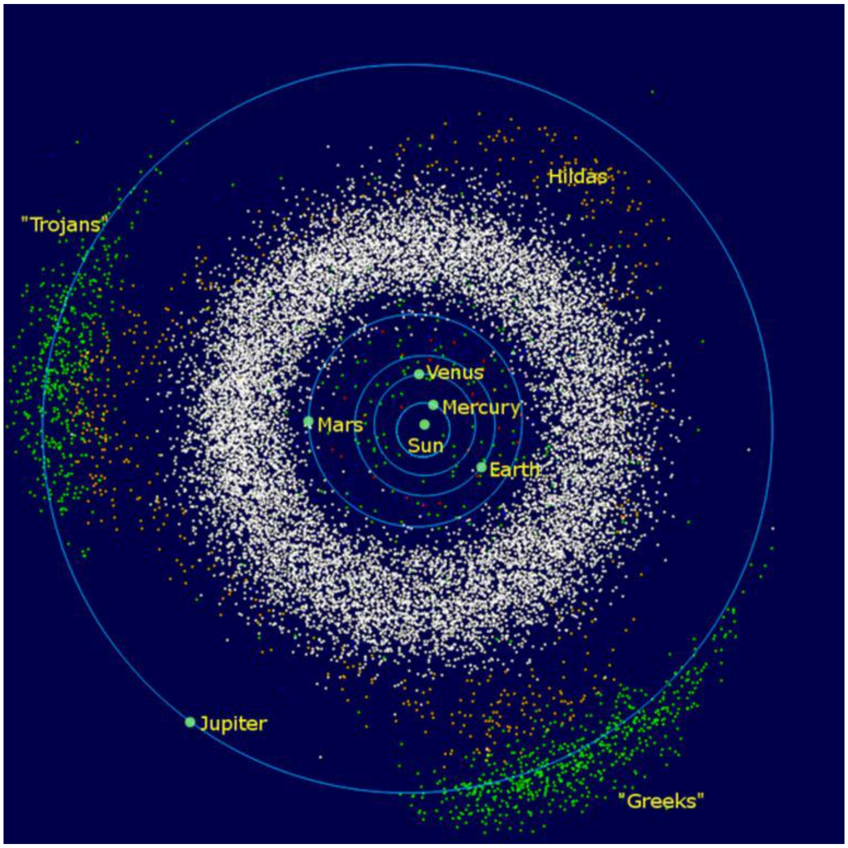

Figure 1-2, Billions of Asteroids in our Solar System [wikipedia]

1.2.1 SMR Approaches:

The historic approach to Space Mineral Resources is in-situ resource utilization. The smart choice is to take an economic [in all forms; financial, mass to lift, mass to operate, mass to protect oneself, and mass to return] approach to space travel by leveraging resources at hand when you arrive at your destination. Two obvious examples are:

- Cover your Lunar habitat with regolith to protect against radiation.
- Recover ice [from lunar craters or Martian sub-surface] to provide fuel, water and oxygen.

To expand beyond the obvious, as an exemplar, Mars can provide CO_2, subsurface water, and water extracted from the atmosphere. A few expected uses are:

1. The broad issue of energy generation. This includes power on the surface and in Mars space. Without adequate energy in space and on the surface of other worlds, any exploration or exploitation enterprise will be impossible. Energy, particularly electrical energy is one of the most easily measured and fungible of resources. In deep space and on the surface of other worlds it is an unassailably essential resource.
2. Grow food for pressurized habitats.
3. Turn the CO_2, through various processes to fabricate radiation reducing habitats, as well as be used as a source of material for additive manufacturing.
4. Propellant and oxidizer for rocket propulsion and rover fuel.

This economic approach to space exploration will enable the human race to expand into the solar system. In fact, this is not just a nice choice; but, a mandatory implementation for future travels beyond LEO. The general layout of expansion into the solar system will be discussed in detail in later chapters; however, for clarity of ideas, it is summarized here with three major approaches for exploiting space mineral resources. One thought is that for the commercial world to make a profit, they have to provide a service. The natural first service would be to provide fuel, oxygen and water for international exploration. This would imply delivery to the customer – probably robotically at first – to Lunar surface facilities, Earth-Moon Lagrangian spaceports, or back to LEO or geosynchronous Earth orbit [GEO] construction facilities.

SMR Approach 1 – Localized Utilization

This will be the initial approach, as it is the simplest, and can leverage early exploration and movement beyond LEO. By gathering and using local resources, missions can be extended. Water, fuel and oxygen could be the first such resources developed [found, moved, processed, stored, and utilized]. The use of such resources has great financial value which can be calculated as costs avoided and mission risks reduced. In time, this SMR Approach 1 will expand and become essential for all human and robotic missions in the future. One concept presumes that commercial ventures may contract with space-faring nations desiring to reduce the cost of initial exploration/habitation missions to the Moon and Mars. These depots could do almost everything to supply indigenous infrastructure for domestic or international exploration missions. These private ventures, located near local resources, provide products to explorers at a fee, which would likely be considerably less than transporting a similar level of capability from Earth. The concept of SMR Approach 1 is to free ourselves of reliance on Earth's infrastructure and supplies as rapidly as possible. This concept is that commercial ventures will be the first to the asteroids, establish a permanent presence on the Moon and Mars, as their mission would be to provide a commercial base station for international and scientific ventures. The motivation to create these spaceports would be a contract with the international entities and organizations for infrastructure and supplies to be used. The sale and use of local resources for habitats, fuel, water, oxygen, propellants, soil to grow food, resources for additive manufacturing would enable large-scale national and international ventures to complete their missions without the requirement to develop their own infrastructures. This is similar to many of history's commercial projects (all initially supported by governments) such as the Hudson Bay Company and the East India company.

The ability to be the first to an asteroid, Moon (as a commercial venture), or Mars under the Hudson Bay , U.S. Air Mail service, or East India Company models, will ensure commercial success as well as support international exploration ventures.

SMR Approach 2 – Transport Materials to Processing Nodes

This concept expands humanity's reach beyond LEO by offering power generation, storage facilities, additive manufacturing, and other capabilities/equipment at appropriate locations. The first activity would likely be energy generation and storage of oxygen, hydrogen, nitrogen[potentially] and carbonaceous materials for water, fuel, propellant, and for plant growth. The beauty of this concept is that the resources and assets needed by the miners, explorers, or colonizers could be in orbit-friendly locations. Some of these locations will be described in subsequent chapters illustrated as Design Reference Missions. Some obvious locations for in-situ resources include:

- Surface of the Moon
- Surface of an asteroid
- Surface of Mars
- Lagrangian Points; Earth Moon EML-1 and EML-2
- In Lunar Orbits
- In Martian Orbit [perhaps on Martian moons]
- In cyclic orbits between Earth and Mars or Earth and the Asteroid Belt
- At the Apex Anchor of either an Earth Space Elevator or a Lunar Elevator

The ability to process SMRs, transport them to a "space depot," and then exploit them for robotic or human travelers will open up the solar system. The concepts surrounding space based depots has been developed over the years and leads to a simple conclusion;

Infrastructure development MUST come before humans venture beyond LEO.

It seems that the first such depot would be the Earth-Moon [EML-1] orbital location where ventures to the Moon and Mars can be staged. This concept uses SMR Approach 1, the in-situ resource leveraging, where supplies are already being created. The next logical step is to move resources towards customers (such as the EML-1 location). International governmental projects can buy supplies at spaceports instead of bringing them up the gravity well.

There are two points of interest that most people focus upon when discussing spaceports for refueling:

- Point One: Most studies end up focusing on water, and its separate components, because it seems to be robustly abundant, extremely useful, and very expensive to deliver from the surface of the Earth. Extracting water would lead to drinking water, agricultural water, oxygen and hydrogen for fuel, and breathable air.

- Point Two: The cooperation between government space projects and commercial ventures could be solidified through a natural "anchor tenant" relationship. Although there is no demand for buying fuel (and water) at any spaceport today, a major incentive for a commercial venture could be immensely enabling by making an offer to purchase a specified quantity at a certain date for a set price.

SMR Approach 3 – Deliver SMRs to Earth's Surface

Previous SMR studies have underappreciated the value of returning resources to humanity because of gravity. The tremendous acceleration towards Earth produces a difficulty well beyond current designs for heat dissipation and control of the asset. Many studies have suggested including regolith and ice as heat shields for product; however, at 25,000 mph return speeds, it seems difficult at best. As such, the future has been fuzzy for the return of resources from deep space or Lunar orbit. One key item that has changed in the last few years is that the International Academy of Astronautics has found that a space elevator "seems" to be feasible. There is much work to be accomplished, and the tether material needed for success has not been developed in great lengths; but, the projections are positive for a future infrastructure that goes up AND DOWN. There is a good discussion on space elevators in the infrastructure chapter. The return of goods and services, as well as resources, has been down-played over the years. However, the value of bringing resources back to Earth greatly enhances the reasons to invest in SMR missions.

With that need in mind, returning SMRs to Earth becomes not only feasible, but desirable. The concept is simple:

- Bring the resources [raw and processed] to the Apex Anchor
- Load onto a down tether climber
- "Climb" down to GEO [100,000 km to 36,000 km altitude]
- "Fall" to Earth in a controlled manner inside a tether climber focused on braking

There will be more details in the systems chapter; but, the concept is simple and its characteristics match up well with SMR missions. The basic concept incorporates slow speeds, soft rides, and safe operations. One expansion of the Earth space elevator concept could be to incorporate a Lunar Elevator. This infrastructure can bring SMRs from the surface of the Moon to EML-1 in a safe and timely manner. Processing could occur at an EML-1 processing plant and then it could be sent on its way to a rendezvous with the Apex Anchor of an Earth space elevator. From there it could be put in a tether climber and delivered to the surface of the Earth.

A reasoned debate can be generated on whether processing materials on the Moon and then transporting to EML-1 is a prudent action. The surface of the Moon has many advantages, not the least of which is some gravity. Gravity is a great organizer. Further, the Moon's mass should protect inhabitants from at least half the radiation dose in EML-1.

There are other approaches for returning processed SMR to the surface of the Earth. Each new approach has been looked at and still concludes that it is difficult. However, the return of SMRs to the surface of the Earth is essential for the full leveraging of our space future.

<u>SMR Approach Summary</u>

The three general approaches for leveraging space minerals break into a logical layout of complexity and infrastructure needs. As humanity moves off-planet, towards the Moon, Mars, and beyond, the utilization of minerals throughout the solar system will be instrumental. At this time, we can not determine which minerals will be the most useful, nor the most troublesome; but, we can conclude that utilizing local minerals for survival, habitat development, or basic refueling will be a great step towards humanity’s expansion. In addition, local resources will be leveraged to provide copious amounts of power.

1.2.2 Brief History of the Space Mineral Resources Concept: The following is a brief background on SMR and the history and development of the concept.

> *“The use of lunar-derived Oxygen was proposed well before the first lunar landing. It has long been recognized that the leverage offered by a propellant source for refueling space vehicles at the lunar surface would dramatically increase space transportation system*

> *effectiveness, and could actually reduce human exploration mission risk by providing a backup air supply for explorers, and a backup propellant supply in case of lander problems. A study by the U.S. Army in 1959 marks the earliest recorded examination of lunar in-situ resource utilization (ISRU) as a critical enabling element of a permanently inhabited underground lunar base:*
>
> *"The maintenance and supply effort to support a lunar base will be high by present standards. Continued delivery of equipment and means of survival will be required and each delivery will be costly. Every conceivable solution for minimizing the logistic effort must be explored. Maximum use of any oxygen or power source on the moon through regenerative or other techniques must be exploited." [Report, US Army, 1959]*

This lunar base study was known as "Project Horizon." In addition to ISRU, the study also marked the first use of the term "commercial" in association with a lunar base. It was applied as a directive for Army personnel to "investigate the scientific, commercial, and military potential of the moon." This ground-breaking report was shortly followed by a second lunar study (the U.S. Air Force's Project LUNEX) which proposed a much more limited touch-and-go lunar expedition [Lunex, 1961].

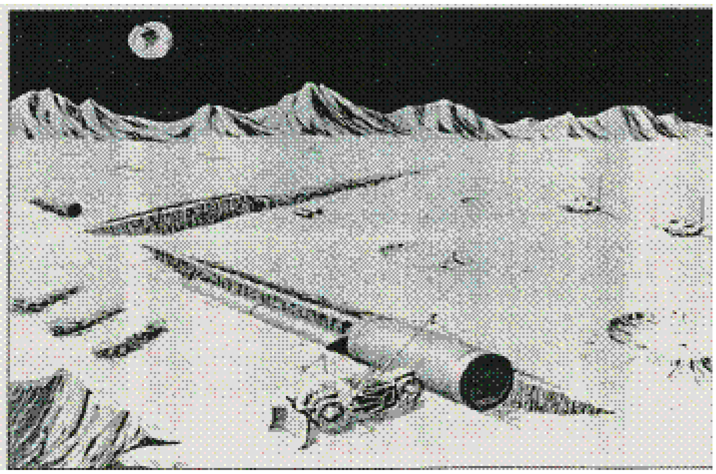

Figure 1.3. Project Horizon image showing burial of lunar habitat module using SMR [US Army, 1959].

Perhaps due to the influence of the Army's more detailed examination of the construction and logistical support requirements for an underground lunar facility, a well-funded ISRU study group suddenly appeared within the newly formed NASA. Portree [2001] summarized their work:

> *"NASA first formally considered ISRU in 1962, when it set up the Working Group on Extraterrestrial Resources (WGER). The WGER, which met throughout the 1960s, focused on lunar resources. ... This was because more data were available on lunar resource potential, and because lunar resource use was, in the Apollo era, potentially more relevant to NASA's activities. ... In the 1960s, ISRU was studied largely in hopes of providing life-support consumables. By the 1980s, the propellant production potential of ISRU predominated. ... ISRU can be defined as using the resources of a place to assist in its exploration — the phrase "living off the land" is essentially synonymous. In the context of space exploration, ISRU enables spacecraft weight minimization. If a spacecraft can, for example, collect propellants at its destination, those propellants need not be transported at great expense from Earth's surface." [Portree, 2001]*

Situational awareness of the chosen destinations is needed because there will be a lot of surprises out there. The number of proposed missions to asteroids, vs. the Moon, is growing. This has a dual benefit for commercial missions as well as for planetary protection. This study will generally describe what is up there and what can be done with it.

For the purpose of an economic comparison, let us limit our discussion to one specific Near Earth Asteroid [Asteroid 1986 DA] made of metal, that was discovered in 1986. It is about two kilometers in diameter, about the size of an open pit copper mine in South America. Just the nickel in this one asteroid is worth about three times the entire national debt of the United States in 2012.

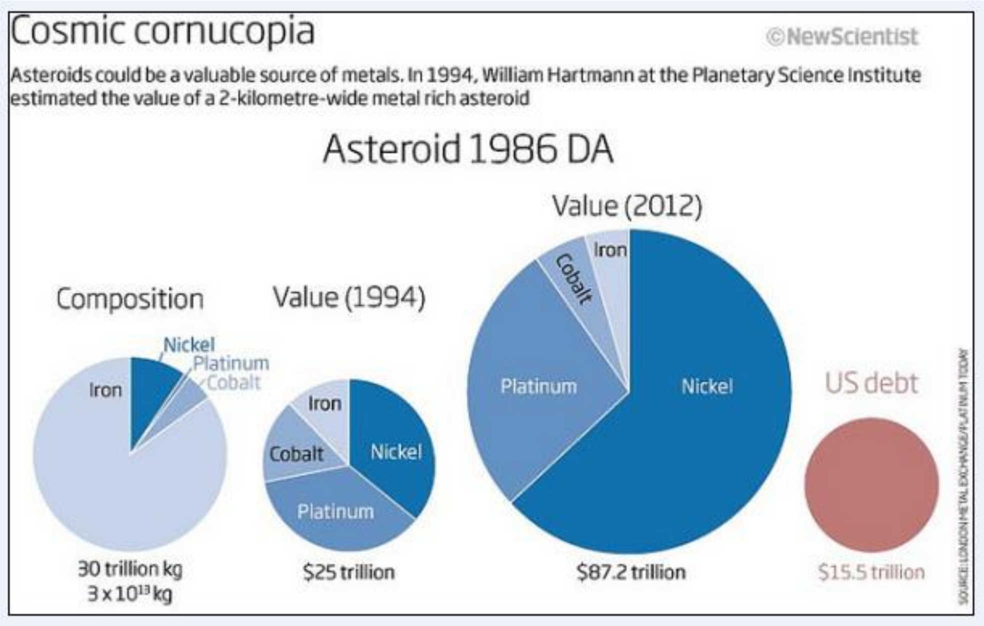

Figure 1-4, Asteroid 1985 DA Value [Hartmann, 1994]

The most valuable near Earth asteroids (NEAs) are those whose orbits closely mimic that of Earth, so that minimal energy is required to reach them and return. More than two million are estimated to exist; yet, only 10,000 have been charted. The list of known NEAs grows by about 1,200 each year and will likely accelerate as additional resources are brought to bear on the task. NEAs are a plentiful resource and the availability of affordable-to-reach targets will continue to expand. Every month a NEA with the potential to end civilization (one km or larger) is discovered; luckily none have orbits that threaten Earth over the next few centuries. Smaller NEAs still can wreak havoc on a regional scale. Currently, the search for NEAs is focused upon the threats to Earth. This global effort is government sponsored with voluntary individual participation from the astronomy community. A thriving space industry seeking NEAs for their resource value could provide the on-going funding required to identify and characterize as many as possible.

1.2.3 Space Mineral Resource Types:

Above the Earth's surface are some tremendous resources, some of which have been extensively used during humanity's adventures into space. The first are the ubiquitous resources present in a majority of the volume of space, especially in the Earth-Moon vicinity. This wide variety of space resources includes solar irradiance and the environment of a vacuum with its heat/cold properties. These resources are valuable and will be exploited by SMR ventures beyond Earth's surface. The next category, orbital locations, is not obvious, but just as valuable. Locations such as low Earth orbit [LEO], geosynchronous Earth orbit [GEO], Lagranian points [L-1 through L-5], low Lunar orbits and Martian orbits will all have strengths that are valuable for commercial ventures into the solar system. The next set of resources comes from the minerals on different bodies in our solar system, to include asteroids, the Moon and Mars with their moons.

Table 1-1, Space Mineral Resource Approaches

Resource Type	SMR #1 In-situ	SMR #2 - transport to location	SMR #3 - to Earth's surface
Ubiquitous	X		
Orbital Location	X		
Asteriod	X	X	X
Lunar	X	X	X
Planetary	X	X	X

Space Resource Type #1 – Ubiquitous

This category of space resource includes the most used one of our history in space, sunshine. In addition, there is the ever present vacuum, and varying levels of heat and cold. These attributes of space have all been leveraged as space resources and will continue to be used by space missions. These are "in-situ" resources leveraged by almost all space players.

Space Resource Type #2 – Orbital Locations

The value of this category is exemplified by the location called GEO. The communications world listened to Sir Arthur C. Clarke as he explained the value of a location in space that is stable over a longitude line on the

Earth. There are currently over 400 commercial communications satellites in GEO "making money." Locations of value include:

Low Earth Orbit [LEO] is valuable for the phenomenal perspective of our Earth with repeating views and communications opportunities. Earth resources satellites, weather satellites, commercial imagery systems and of course, the International Space Station exist in this range.

Geosynchronous Earth Orbit [GEO] is the historically successful communications and weather location around Earth.

Earth-Moon [EML-1] will be a valuable location as a spaceport and way station for future solar system flights, as well as for lunar missions. L-1 is a partially stable location with easy access in our Earth Moon ecosphere.

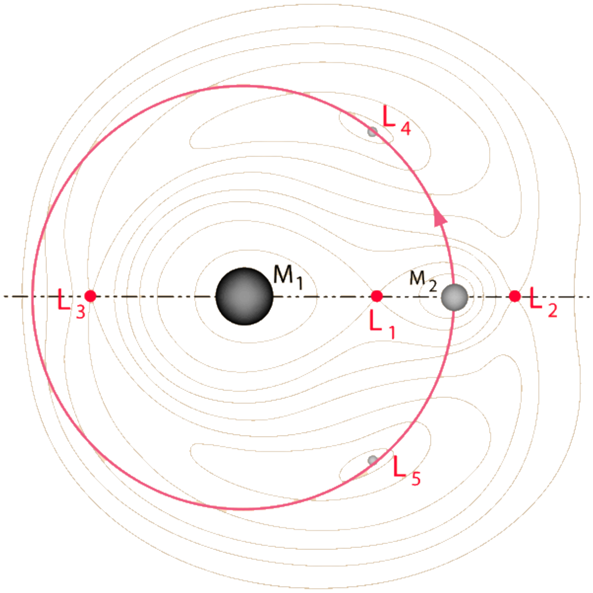

Figure 1-5, Lagrange Points Earth Moon System
[http://hyperphysics.phy-astr.gsu.edu]

Low Lunar Orbit (LLO) will provide the same type of characteristics as LEOs, but around the Moon.

Low Martian Orbits (LMO) will provide similar strengths to LEOs and LLOs. In addition, sitting on moons of Mars will provide the strength of location which could be of value to commercial space ventures in the future.

Space Resource Type #3 – Asteroid

This category of space resource has phenomenal mineral diversity as well as one of the greatest threats to humanity. The threat is beginning to be addressed while their potential commercial value is estimated to be huge.

> *"Asteroids represent a significant potential resource of raw materials, both in support of continued space exploration activities and for the wider global economy (e.g. Martin, 1985; Hartmann, 1986; Lewis et al., 1993). Many NEAs are relatively easy to reach in energy terms and have very low surface gravities, which would minimize the cost of transferring materials extracted from them to the vicinity of the Earth. Moreover, for many of these objects nature has already performed significant refining, or at least beneficiation, for us. For example, metallic asteroids (which constitute a few percent of the NEA population) consist of essentially pure nickel-iron alloy, and although Earth has significant reserves of both these elements they may still be very useful in the context of future space development. Perhaps of greater interest is the fact that metallic asteroids also contain about one hundred parts per million of gold and platinum group elements (PGEs), which are of sufficiently high value (for example as industrial catalysts) that they may be worth importing directly to Earth (e.g. Kargel, 1994). At today's prices for these elements ($20,000 to $50,000 per kilogram) it follows that a single small metallic asteroid about 200 metres across could be worth of the order of $100 billion dollars. Thus, in addition to being metaphorical scientific gold mines, some asteroids may prove to be literal gold mines as well! Moreover, although essentially rocky objects, ordinary chondritic asteroids (which probably account for the majority of NEAs) themselves consist of several percent Ni-Fe metal, which similarly contains hundred ppm-levels of PGEs. In addition, carbonaceous chondrites (which make up perhaps 10-15% of NEAs) are relatively rich in volatiles, which could be of great value to a future space economy by providing water, hydrogen, and oxygen for future space missions without the need to haul these materials*

> *out of Earth's gravity. Last but not least, there are also strong environmental arguments for mining even relatively common materials (such as iron, nickel, copper, and the increasingly important rare earth elements) from asteroids as an alternative to invasive strip-mining on Earth – asteroids do not have indigenous ecosystems that may be disrupted by mining activities whereas our planet does (see the discussion by Hartmann, 1986). For all these reasons, developing the capability of extracting useful resources from asteroids, and from other extraterrestrial sources, can be seen as an important investment in the future of the world economy (e.g. Crawford, 1995)."* [Crawford, 2013]

Due to a lack of a generalized explanation as well as promotion, few people understand the basic parametrics of Space Mineral Resources (SMR). This study is intended as a remedy to that situation. Everything on Earth, without exception, can be found more plentifully (by several orders of magnitude) in space. An example is hydrocarbon lakes on Titan or purified ice in the rings of Saturn. Many other examples exist, including Haley's Comet – which contains nearly the same hydrocarbon inventory as the proven reserves of all of the OPEC nations combined, in addition to more water than Lake Michigan. The next question becomes – which space resources are "close" to utility?

> *"Indigenous Space Materials Utilization (ISMU --formerly called In-Situ Resource Utilization) can provide a reduction in cost and can increase our capabilities significantly as we develop and expand a lunar or Mars outpost. Our goal for the ISMU program is to free these outposts from total reliance on the Earth as soon as possible, thereby rapidly shifting the nature of our space transported cargo away from bulk materials, such as propellants and building materials, to additional people and complex equipment."* [Sullivan et al, 1991]

A paper at the AIAA Space 2013 Conference entitled "Asteroid Mining," presented the breakout of asteroid product well.

> "The Hierarchy of Resources and Markets shows that in general, the resources obtainable from asteroids can be divided into 4 broad categories: free water, bound water, metals, and regolith.

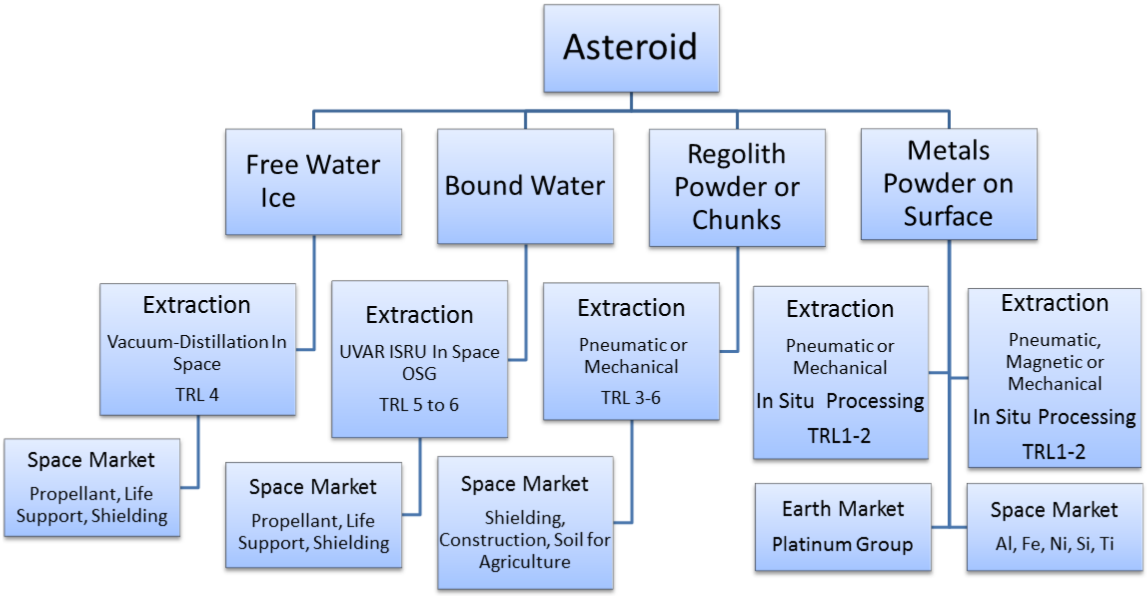

Figure 1-6. The Hierarchy of Space Resource Extraction and Markets. (Zacny, 2013)

> "It is a standard practice for terrestrial mines to organize mining operations around the main mineral product, while collecting bonus revenues from 'byproducts' of lesser concentration. In a similar vein, we will not travel all the way to an asteroid to mine just one resource." [Zacny, 2013]

Space Resource Type #4 – Lunar Surface

This category of space resources includes locations where we have actually been. This time, the plan is to use the resources instead of just picking them up. Extensive research was conducted on how to use lunar resources to support lunar base activities [see WGER, 1962-1970]. Ideas captured in these early conference proceedings included many of the foundational concepts for modern ISRU. This work continued through the Apollo era and into the 1970s and 1980s. It was lead by a small group of lunar scientists and engineers at NASA's Johnson Space Center (JSC), home of the lunar sample collection and many prominent members of the planetary science community. The Apollo missions brought back enough lunar rock and soil samples to firmly establish the Moon's geologic character, particularly in the equatorial regions where the landings took place. Two publications that summarize much of the ISRU research during this era can be found in Mendell, [1985] and McKay, [1992]. A well-funded NASA study by General Dynamics examined the potential construction of a large-scale space solar power system using lunar resources [Bock, 1979]. Eagle Engineering, Inc. later conducted another important and highly detailed set of ISRU and reusable spacecraft design studies for NASA JSC [Davis, 1988].

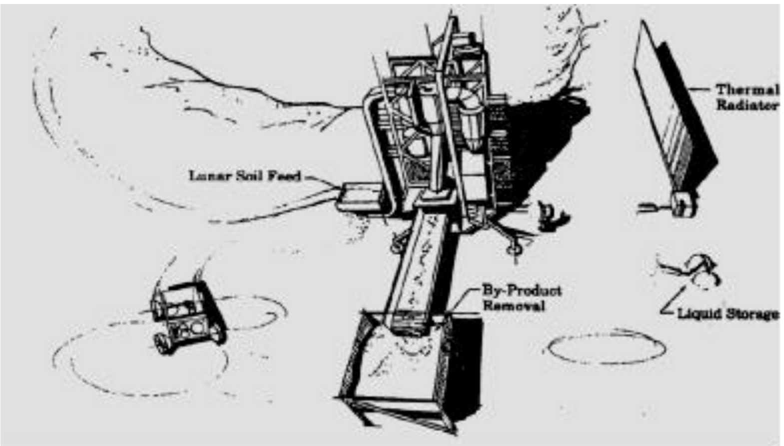

Figure 1.7. Conceptual layout of Lunox production plant [Davis, 1988].

The value of learning to "live off the land" was acknowledged by U.S. President George H. W. Bush when calling for a "return to the Moon, this time to stay" in 1989. The ensuing Moon / Mars exploration effort, spearheaded by NASA, became known as the Space Exploration Initiative (SEI) and sponsored a series of lunar architecture design efforts within and around the NASA community [see Lindroos, 2008]. One lunar base design (a 1993 NASA-JSC lunar architecture named LUNOX) assumed ISRU as a core element. This design drew heavily on the modeling work of Davis [1988], which created parametric estimating relationships to predict the mass and power consumption for future lunar excavation and materials processing elements. Sadly, SEI's days were short lived as the elder President Bush's administration faced an economic recession, which turned Congress against the costly program. The result was a dramatically reduced level of US Government funding for human space exploration design studies, as well as supporting technologies such as ISRU. This changed again in 2004 when the goal of returning to the Moon and using lunar resources was stated with stunning clarity by U.S. President George W. Bush:

> *"Returning to the moon is an important step for our space program. Establishing an extended human presence on the moon could vastly reduce the costs of further space exploration, making possible ever*

> *more ambitious missions. Lifting heavy spacecraft and fuel out of the Earth's gravity is expensive. Spacecraft assembled and provisioned on the moon could escape its far lower gravity using far less energy, and thus, far less cost. Also, the moon is home to abundant resources. Its soil contains raw materials that might be harvested and processed into rocket fuel or breathable air. We can use our time on the moon to develop and test new approaches and technologies and systems that will allow us to function in other, more challenging environments." [Bush, 2004]*
>
> *"The result of this challenge ushered in a new renaissance of ISRU work within the US civilian space agency, and extending to universities, corporations and international partners, primarily due to the necessary entanglement between mining, chemical processing, manufacturing and aerospace technology required to make ISRU effective and robust. Ongoing research has received stronger financial support from NASA than ever before, including formulation of ISRU mission requirements to guide the agency's investment. Extensive literature now clearly identifies the potential benefits of ISRU. Concepts have become engineering models, which are now gathering support by a growing amount of information from hardware subsystem-level prototypes. However, current NASA Lunar Architecture requirements have carefully avoided placing ISRU in the critical path, and have therefore limited stating or publishing ISRU goals and milestones to a relatively limited set of late-term demonstration capabilities that start well after humans arrive [Sanders, 2007a]. This approach defers most of the benefits of ISRU technology and capabilities to downstream missions, locking the lunar architecture into a wasteful and expensive approach and therefore increasing program as well as mission risk."* [Baiden & Blair, 2009]

Space Resource Type #5 – A current example of SMR discovery mission is the Chinese Yutu lunar rover [also called the Jade Rabbit].

The scientific objectives of the lunar rover are to understand the surface topography and conduct a surface material composition survey. The next image shows the Jade Rabbit on the Moon in a picture taken from its lander.

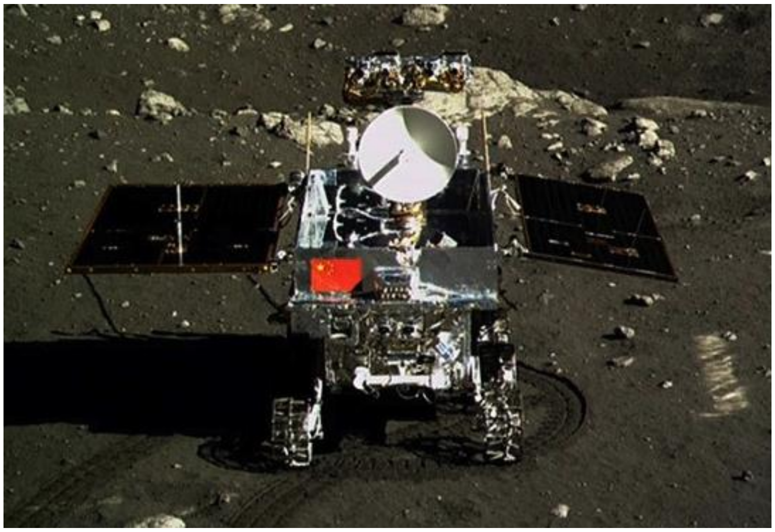

Figure 1-8, Jade Rabbit on the Moon[1]

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[1] *See* Wikipedia, Yutu(rover), http://en.wikipedia.org/wiki/Yutu_(rover), (as of June 9, 2015 12:00 GMT).

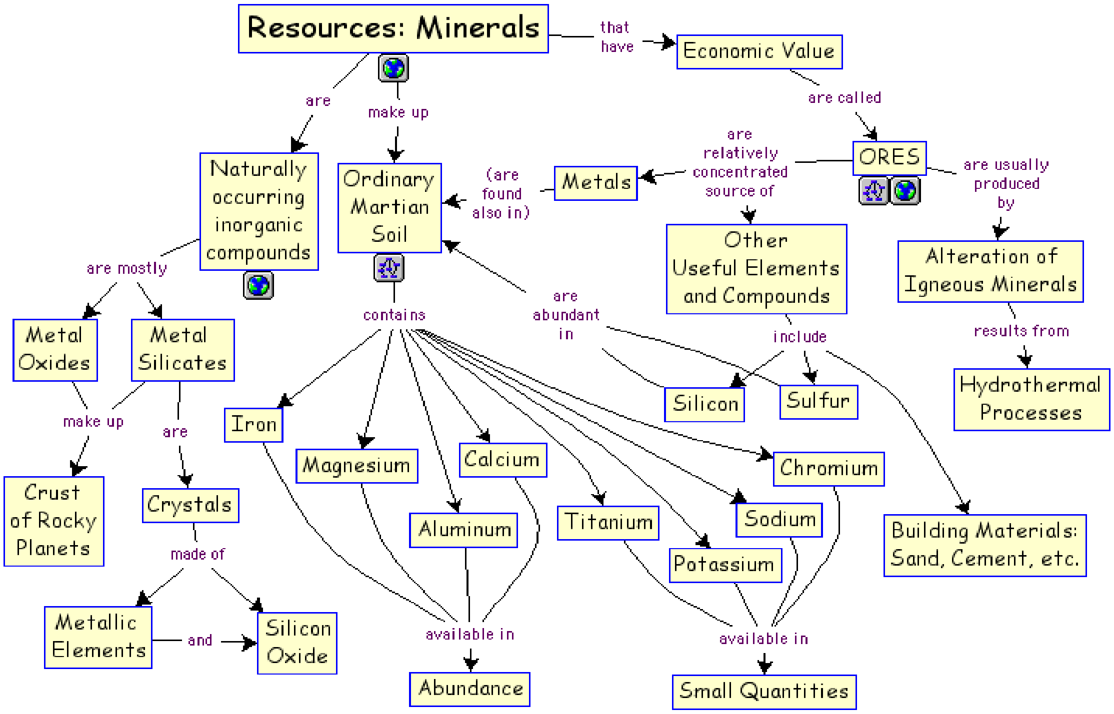

Figure 1-9, Mars Mineral Resources[2]

Commercial Roadmaps: To provide an understanding of "how to" achieve commercial viability on space mineral resource development, four company SMR roadmaps will be shown. Chapter Four will lay out the approaches that each of these companies has taken.

- Deep Space Industries
- Shackleton Energy Company
- Planetary Resources
- Excalibur Exploration

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[2] Mars Mineral Resources, *available at* http://reseauconceptuel.umontreal.ca/rid=1225319082132_441683932_76782/Mineral%20Resources.cmap.

1.3 Legal and Policy Summary:

The key conclusion from this study is that commercial SMR activities are legal. There have been many recent discussions on this topic in many conferences as more and more people are looking to support space mineral resource projects. The chapter on Law and Policy will address the international issues and the treaties in place that deal with SMR activities. Philip Harris, in his article "Space Law and Space Resources," summarized it pretty well with:

"The official position of the United States. clearly enunciated in the debates of UNCOPUOS, interprets these provisions to permit any nation or corporation to mine and otherwise use the resources of outer space…… Even under the rather anti-capitalist Moon Treaty, the official position of the U.S. negotiators in UNCOPUOS has been that the treaty permitted companies and nations to mine the Moon. For instance, light elements hydrogen, nitrogen, and carbon-exist in limited quantities in the lunar soil, and frozen water may exist in larger amounts at the lunar poles. Under the longstanding U.S. legal interpretation, the nation finding these resources will be able to mine them. The nation will not own the site, but its labor will attach ownership to the ore." [Harris]

1.4 Governance:

Space resources, both mineral resources and space solar power, will be much more important to the developing world than to the developed world. This is because the developed world already has 96% of the world's wealth. They're not likely to share this in any meaningful way absent a massive war. Anyone who reads history knows this to be true. The 4 billion people in the developing world, comprising 60% of the world's population, only have 6% of this world's wealth. Their answers must come from space.

The developed world can contribute technology, debt, and equity financing for space development. The developing world can provide human resources, engineering, management and genius. At least 50% of the total cost of any space project is human resources. The developing world doesn't need charity. Charity won't work in the long run. They can be equal partners and receive a full share of the benefits by providing human resources to these space development projects. To do this, they must begin Science, Technology, Engineering and Mathematics (STEM) education in their high schools and colleges; otherwise, they won't have the human capital to invest.

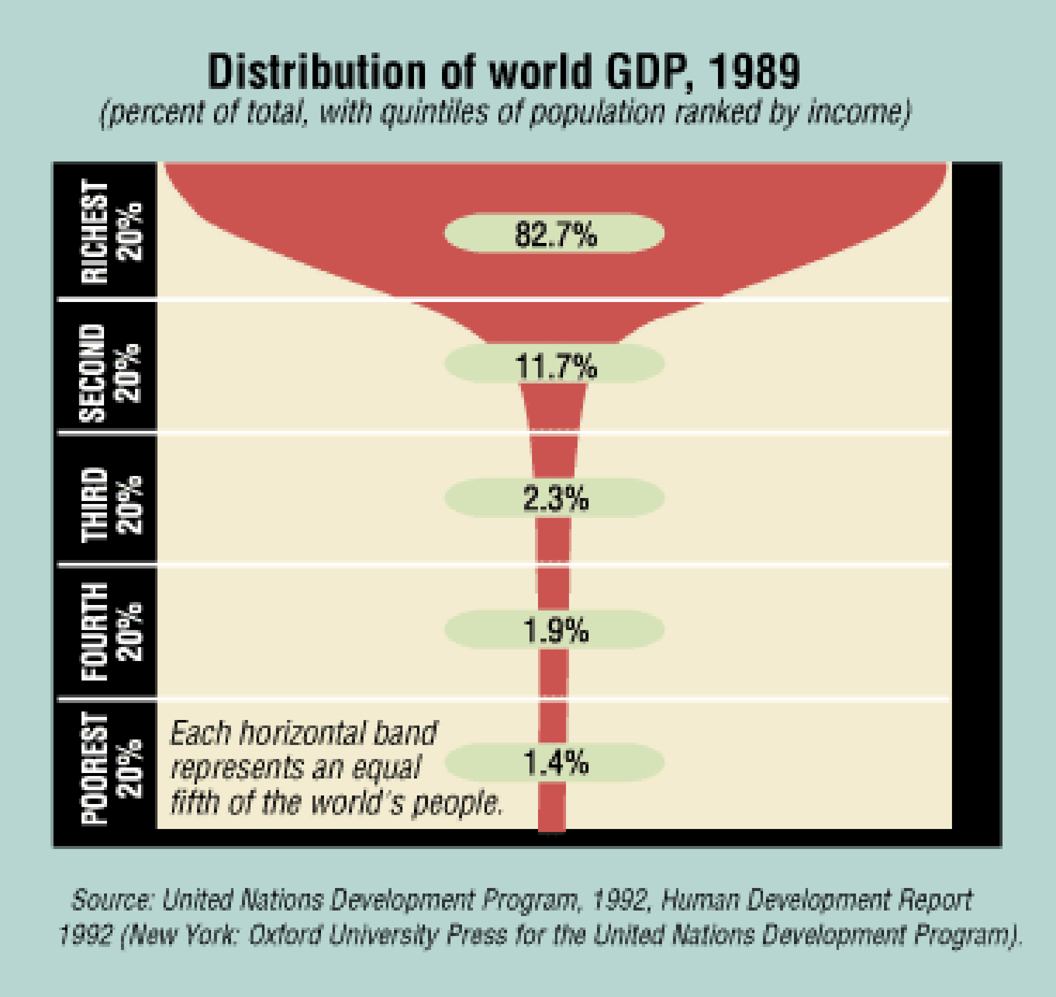


Figure 1-10, Distribution of Wealth [Human Dev Report, 1992]

Anyone who proposes a model of governance for space projects must be very careful to make sure that unnecessary impediments are not put in the way of innovative activities between the developed and developing world. No prior model in history is adequate for this. It will be cut from new cloth. Small minds may attempt to regulate everything in advance of reality.

1.5 The International Academy of Astronautics (IAA) Study:

The purpose of this study is to provide, in one document, the current state of the art of the technology, economics, law & policy related to Space Mineral Resource opportunities. This study will also make specific recommendations for moving forward. The Academy is an elected member based organization composed of global space experts who continue to contribute to the future. [see Appendix G] This is just one of many on-going studies by the organization. This study has the following goal:

To provide a logical, systematic and practical road map to promote and encourage near term evaluation, development and use of space mineral resources (SMR).

Although some books, and/or scholarly and popular papers, have been published on space mineral resources; to the best of the authors' knowledge, no comprehensive summary of the current literature on this subject is now publicly available. Unlike space solar power, space mineral resources has not been the subject of recent government or industry funded studies. This IAA study would be the first comprehensive study of the subject; and, thus it should be of significant value to its development for the benefit of humanity.

1.5.1 Organization of this Report:

This study is organized to provide technical information, policy and legal analyses, economic context and opportunity analyses, and recommended steps for moving forward. Finally, an international roadmap showing pathways forward is offered. Following this roadmap will maximize the rate and likelihood of SMR development, as well as have the corollary benefit of saving humanity from one or more potential civilization or species-ending disasters. The layout of the study report is structured across a logical sequence:

First – Set the stage; general background and then “how to mine.”
Second – Describe the market and potential roadmaps to profit
Third – Look at the technologies necessary to achieve success
Forth – Conduct analysis between choices
Fifth – Assess the legal, policy and governance issues
Sixth – Summarize conclusions and recommendations

Chapter 1 Introduction: This chapter shows the ideas expanded upon throughout the document, as well as, a description of space mineral resource approaches and a listing of the types of resources being sought. In addition, some quick insights are shown to set the stage for the rest of the report.

Chapter 2 Mining of Space Resources: This chapter will show the mineral content of likely locations for mining and processing materials as well as discussions of the processes and the technological equipment needed. Asteroids have tremendous potential; but, each is different and needs to be understood prior to approaching. Planetary surfaces provide a spectrum of mineral resources; but, where and how to develop them is the question.

Chapter 3 Market Approach: This chapter will look at financial approaches to ensure commercial success. Economic models will look at not only the value of the minerals to be mined, but the investment required to get there, provide mining facilities, store the resources, and then transport them to the customer.

Chapter 4 Roadmaps for SMR Development: This chapter will look at the four principle roadmaps that are being developed. The fact that these are being shown by companies with assets and plans to invest sizable amounts of funding into their chosen approach is remarkable. Each roadmap will illustrate their similarities and differences.

Chapter 5 Quick Look at SMR Systems: This chapter will analyze the systems aspects of these solar system level ventures. It will help identify the various risks that much be understood and mitigated. Technologies will be assessed as to their level of readiness for space with the traditional NASA Technology Readiness Level [TRL] approach and rating. In the end, this will assess the technological feasibility of the effort to provide a profit for SMR commercial ventures.

Chapter 6 Modeling and Analysis: This chapter will look at the needs of commercial venders in understanding the issues. In addition, the modeling and analyses will help ventures understand where to invest near term funding to create a successful venture.

Chapter 7 SMR Policy, Legal and Other Considerations: This chapter will analyze international treaties and policies around the world for operations in space.

Chapter 8 Findings, Conclusions & Recommendations: This chapter will consolidate the findings and lead to the report's conclusions and recommendations.

Chapter 9 Concept for the Future – Water is the Currency for Space: This is a brief extrapolation towards the future recognizing the importance of mining water.

References and Index

Appendices: IAA Study Participants, Glossary of Acronyms, Study Terms of Reference, Need for Water, Need for Nickel, Strategic Global Scenarios, and IAA Description

Chapter Two – Mining of Space Resources

2.0 Introduction

The three SMR Approaches set the stage for mining, processing and deploying resources from around our solar system. The basic question is what minerals and resources are available at in-situ collection sites. This chapter will focus on SMR Approach 1, In-situ utilization, as the ability to live off the terrain where the robot or human has landed. The chapter will look at active commercial SMR companies, benefits of SMR, processing of ores, and a summary of in-situ space resource mining. The essence of a "commercial venture" is to make a profit; so, this chapter will be emphasizing the valuable resources that can be utilized during our expansion into space.

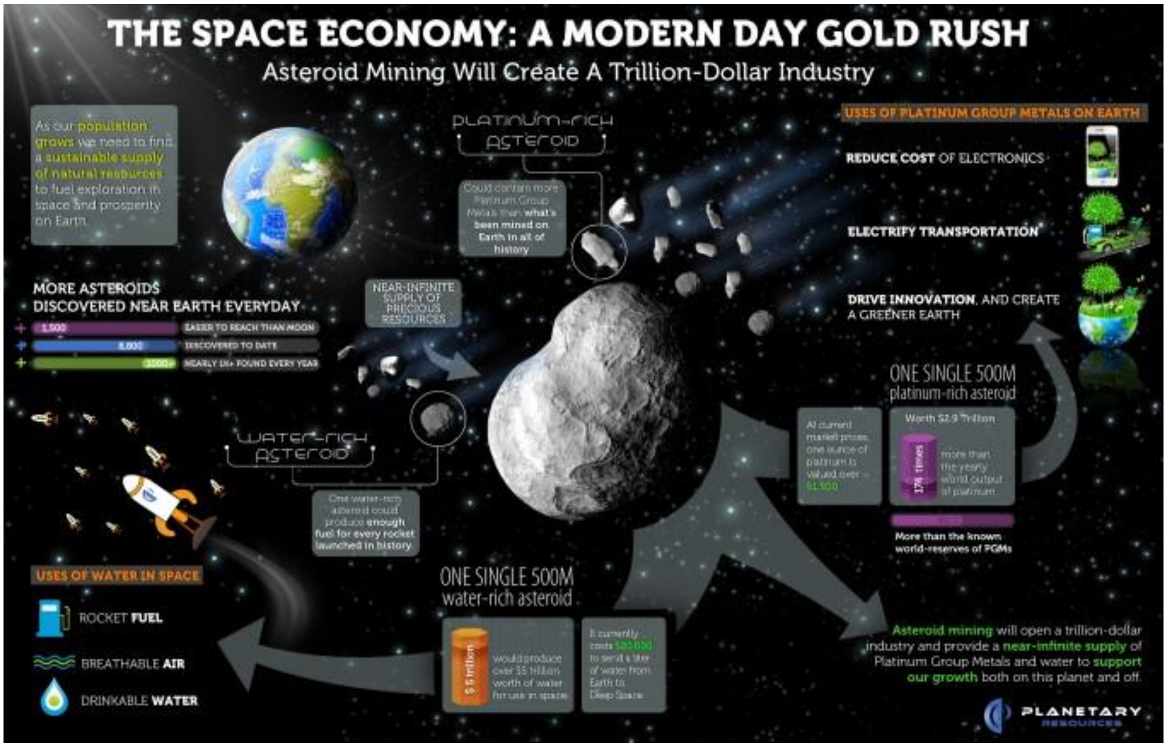


Figure 2-1, Future Space Economy Scenarios Enabled by Asteroid SMR (courtesy Planetary Resources)

2.1 Study Report Exemplars

During this study report, two examples will be used for the reader to identify the benefits, difficulties and advantages of SMRs from space. Each of these examples will be expanded upon during the entire report; but, each stands alone as a descriptor of the concepts available in future SMR arenas.

Water to Earth—Moon EML-1: This example is simple. Find, mine, process, store, and transport water to a location of value, such as the EML-1 staging location where a fuel depot will be available. This resource is perceived to be the "low hanging fruit" of SMRs with the ability to find abundant products on the Moon and asteroids. The concept is to find ice and provide products to customers at a staging location for future solar system travel. Ice can be refined into fuel [Oxygen-Hydrogen], water, air [with some additions], and shielding for the EML-1 Fuel Depot. Customers will include all explorers [and robotic expeditions] who would prefer to buy less expensive fuel at EML-1 vs. transporting fuel against the gravity well of the Earth. Rockets have mass limits; and, if fuel could be purchased elsewhere, more payload can be launched. The value of water at EML-1 will be derived from the cost to raise water from the surface of the Earth to EML-1. This would range in cost according to launch capabilities; however, a simplistic approach is shown in a future chapter with a number somewhere in the range of $ 20 million [US] per ton of water, if delivered from Earth to EML-1. Therefore, delivery from an asteroid or from the surface of the Moon has a price goal of production and delivery at less than $ 20,000 per kg.

Nickel to Earth's Surface: The value of delivering minerals to the surface of the Earth comes from the quantity and availability of the resources in space. The price is always set by the commodity's markets and is relatively stable in the long run. As resources are more difficult to find and process, the price goes up. SMR ventures must trade off the amount of material they are able to deliver to the market vs. the cost of mining an asteroid or the surface of the Moon. As such, if the SMR community establishes a price-point of 80% of a future commodity's price [estimate ten years in the future], they would have an estimate of the revenue potential of bringing back a ton of minerals. The case this study uses is Nickel. It could be platinum or diamonds; but, the study chose a stable material with a known commodity price to help identify revenue potential for future ventures. The going price for Nickel, as of the summer of 2014, is roughly $ 8.14 per pound [or $ 17, 930 per metric ton].

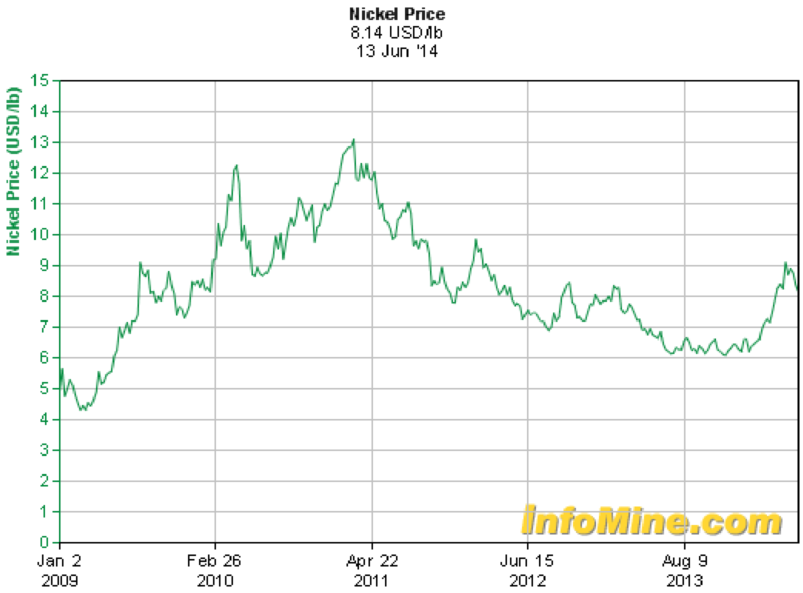


Figure 2-2, Nickel Price 8.14 USD/lb, 13 June 2014 [www.infomine.com]

2.2 Commercial Projects of Today

Within the last decade, a number of private initiatives have surfaced promoting private space exploration and development. The emphasis on commercial is definitely a 21st Century initiative providing exciting times for New Space companies. Recently United States Congressman John Culberson illustrated why governments should go commercial, and when.

> "I've always been a big believer in the Yellow Pages test: If you can find a service in the Yellow Pages that the government provides, you should privatize it, if at all possible." [Culbertson, 2014]

In many countries there are policies about commercial space activities. One such nascent policy is funding the beginning of commercial flights supporting the International Space Station (ISS). This includes Orbital Sciences and SpaceX for resupply and Boeing and SpaceX for human taxi services to the ISS. There is also the realization that commercial spacecraft are going to take passengers to the edge of space. All of these commercial ventures are currently covered under a single national policy, but others are following suit; ie. United Kingdom and their proposed spaceports.

During this embryonic phase of commercial services to space, the NASA and FAA have cooperative agreements which are consistent with the National Space Policy of the United States of America (June 28, 2010). This policy directs federal agencies to:

> "… minimize, as much as possible, the regulatory burden for commercial space activities and ensure that the regulatory environment for licensing space activities is timely and responsive;" and
> "…pursue potential opportunities for transferring routine, operational space functions to the commercial space sector where beneficial and cost effective…"

A partial list of companies interested in SMR is shown below while being broken into categories; commercial lunar development, asteroid development, Mars ventures, and tether/elevators.

2.2.1 Commercial Lunar Development Companies

<u>Golden Spike</u> The Golden Spike Company is planning to transform human space exploration by putting in place affordably priced lunar orbital and surface expeditions to the only natural satellite of the Earth – the Moon. Golden Spike will further transform human lunar exploration by making these missions participatory expeditions that involve the general public in ways that create exciting new ways to monetize human space exploration. The Golden Spike Company has been formed to monetize the exploration of the Moon through sales of expeditions and their surrounding media and merchandizing revenues. [from their website]

<u>Shackleton Energy Co</u> Fueling the Space Frontier, as 95% of mass going beyond LEO is fuel, it would be profitable to have a fuel depot in

Earth orbit, with an objective of low cost fuel from the Moon. [from their website]

Moon Express Believing it's critical for humanity to become a multi-world species and that our sister world, the Moon, is an eighth continent holding vast resources that can help us enrich and secure our future. The Moon is unique in that its surface has remained relatively constant over billions of years. Most of the elements that are rare on Earth are believed to have originated from space, and are largely on the surface of the Moon. Reaching for the Moon in a new paradigm of commercial economic endeavor is key to unlocking knowledge and resources that will help propel us into our future as a space faring species. [from their website]

Excalibur Almaz A n international commercial space transportation company based in the Isle of Man. Its goal is the affordable and reliable transportation of humans and cargo to Low Earth Orbit, Lagrangian point, the Moon and beyond. EA is building a private space program, starting with a transportation system using proven equipment and launch services. The company's goal is lunar exploration, Lagrangian point missions, asteroid mining and other long term business in space. Excalibur Almaz can accomplish customer requirements at lower costs, achieving operational objectives in reduced time with lessened risk of safety issues, regulatory constraints and liability challenges, by using proven heritage hardware. Excalibur Almaz's goal is to create affordable commercial space transportation to Low Earth Orbit, Lunar Orbit, Near Earth Objects and deep space. [from their website]

Bigelow Aerospace Aims to provide affordable options for spaceflight to national space agencies and corporate clients. In 2006 and 2007, Bigelow launched the orbiting prototypes Genesis I and Genesis II. Using their patented expandable habitats, Bigelow's plan is to greatly exceed the usable space of the International Space Station at a fraction of the cost by developing their next generation spacecraft. With over ten years of research and development, Bigelow is dedicated to providing affordable options for spaceflight to national space agencies and corporate clients. [from their website]

2.2.2 Asteroid Development Companies:

Planetary Resources Inc Planetary Resources is bringing the natural resources of space within humanity's economic sphere of influence, propelling our future into the 21st century and beyond. Water from asteroids will fuel the in-space economy, and rare metals will increase Earth's GDP. Planetary Resources' mission is clear: apply commercial, innovative techniques to explore space. They plan to develop low-cost robotic spacecraft to explore the thousands of resource-rich asteroids within our reach and learn everything they can about them, then develop the most efficient capabilities to deliver these resources directly to both space-based and terrestrial customers. Asteroid mining may sound like fiction, but it's just science. There are near-limitless numbers of asteroids and more being discovered every year. More than 1,500 are as easy to reach as the Moon and are in similar orbits as Earth. Asteroids are filled with precious resources, everything from water to platinum. Harnessing valuable minerals from a practically infinite source will provide stability on Earth, increase humanity's prosperity, and help establish and maintain human presence in space. [from their website]

Deep Space Industries The riches of the solar system offer humanity both unprecedented prosperity and an improved environment. The resource potential of space outstrips that of any previous frontier - without the environmental impacts. Asteroids are plentiful throughout the solar system. Many orbit close to the Earth and many of these carry vast deposits of resources ranging from water to metals such as iron, gold and platinum – everything we need to expand our civilization into space, to provide for our needs here at home and to increase the wealth of our planetary economy. In addition, the sun shines 24/7 in space, and the electricity beamed to Earth from solar power satellites is carbon-free and leaves no radioactive waste. With the effects of gravity at a minimum, we can do amazing things when it comes to moving, construction, and innovations in chemistry and physics. In fact, we are limited only by our own imaginations. All of this in a place safely outside of our delicate biosphere. Deep Space Industries believes the human race is ready to begin harvesting the resources of space both for their use in space and to increase the wealth and prosperity of the people of planet Earth. Their philosophy is to drive towards the achievement of this guiding vision while securing a strong reputation as a credible, nimble and profitable commercial space operations, mining and manufacturing firm, with a no-nonsense, high integrity can do attitude. DSI will build on the incredible heritage of the first age of space exploration and harness the power of a new age of information to locate, explore, harvest and utilize the vast numbers of asteroids in Earth's community. They will do so by being creative and practical – taking small steps to begin with, and giant leaps when we can – to new and hopeful future for humanity. [from their website]

__Excalibur Exploration__ Excalibur's purpose is to conduct space exploration and resource development and to do all other things that are legal and necessary to accomplish this purpose. Excalibur Exploration Limited (EE or Excalibur) was founded on May 4, 2007, as an Isle of Man Corporation. The company is 100% owned by Excalibur Limited, also an Isle of Man Corporation, which, in turn, is owned by two Americans. Excalibur Exploration Limited was to be the exploration component of this commercial space activity. The Isle of Man was chosen as a corporate venue for two reasons: it has zero tax for space activities and space activities on the Isle of Man are controlled by the United Kingdom's 1986 Outer Space Act. This Act, unlike the American law, permits the Isle of Man government to specifically license and authorize "any activity that may be conducted in outer space." The Isle of Man government, in coordination with United Kingdom government, is a corporate venue whose laws and regulations permit issue of a license for space mining and for the return of materials mined in space to the surface of the Earth. It is very important to take note that many of the risks and barriers faced by any company that wishes to engage in commercial space mining are legal, administrative and regulatory; not technical. The full spectrum of such risks must be addressed by Excalibur as a priority action in its business development. [from their website]

2.2.3 Commercial Mars Development Companies

__SpaceX__ SpaceX designs, manufactures and launches advanced rockets and spacecraft. Its owner, Elon Musk, has stated numerous times that he would like to see 10,000 humans on Mars in his lifetime. The company was founded in 2002 to revolutionize space technology, with the ultimate goal of enabling people to live on other planets. Under a $1.6 billion contract with NASA, SpaceX will fly numerous cargo resupply missions to the ISS, for a total of at least 12 —and in the near future, SpaceX will carry crew as well. Dragon was designed from the outset to carry astronauts and now, under a $440 million agreement with NASA, SpaceX is making modifications to make Dragon crew-ready. SpaceX is the world's fastest-growing provider of launch services. Profitable and cash-flow positive, the company has nearly 50 launches on its manifest, representing close to $5 billion in contracts. These include commercial satellite launches as well as NASA missions. Currently under development is the Falcon Heavy, which will be the world's most powerful rocket. All the while, SpaceX continues to work toward one of its key goals—developing reusable rockets, a feat that will transform space exploration by delivering highly reliable vehicles at radically reduced costs. [much of this from their website]

Inspiration Mars Mars presents a challenging, but attainable goal for advancing human experience and knowledge. Inspiration Mars plans to launch "A Mission for America" that will use existing space transportation hardware and further drive technology development. It will generate knowledge, experience and momentum for the next great era of space exploration. It will encourage and embolden all Americans to believe again, in doing the hard things that make our nation great, while inspiring the next generation of explorers to pursue their destiny through STEM education and exploration. Now is the time! In 2018, the planets will literally align, offering a unique orbit opportunity to travel to Mars and back to Earth in only 501 days. Inspiration Mars is committed to sending a two-person American crew – a man and a woman – on an historic journey to fly within 100 miles around the Red Planet and return to Earth safely.
The mission's target launch date is Jan. 5, 2018. This exceptionally quick, free-return orbit opportunity occurs twice every 15 years. After 2018, the next opportunity won't occur again until 2031. The mission will provide a platform for unprecedented science, engineering and education opportunities, using state-of-the-art technologies derived from NASA and the International Space Station. It will be financed primarily through philanthropic donations, with some potential support from government sources.
This mission will be a flyby passing within 100 miles of the surface of Mars. Additional maneuvers will be minor course corrections only, using the gravitational influence of Mars to "slingshot" the vehicle onto a return course to Earth. An inflatable habitat module will be deployed

after launch and detached prior to re-entry. Investments in human space exploration technologies and operations by NASA and the space industry are converging in time to make such a mission achievable. The mission is being designed based on proven Low-Earth Orbit (LEO) systems and technologies that are available on the market today. This mission will showcase American innovation at its best, generating knowledge, experience and momentum for the next great era of space exploration. It represents an unprecedented, long-duration research opportunity that will lead to new, cutting-edge discoveries. It validates decades of taxpayer investment in NASA technology and strengthens the United States' position as a leader in exploration. It inspires the next generation of explorers to pursue their destiny through STEM education. This mission is the ultimate demonstration of our collective space exploration capabilities to date. [from their website]

Mars ONE Mars One will establish a permanent human settlement on Mars. Crews of four will depart every two years, starting in 2024. Their first unmanned mission will be launched in 2018. Foundations of mission plans, accomplished in 2011 by Bas Lansdorp and Arno Wielders, lay the foundation of the Mars One mission plan. Discussion meetings are held with potential suppliers of aerospace components in USA, Canada, Italy and United Kingdom. Mission architecture, budgets and timelines are solidified from feedback of supplier engineers and business developers. A baseline design for a mission of permanent human settlement on Mars achievable with existing technology is the result. [from their website]

2.2.4 Space Elevator and Tether Companies

Tethers Unlimited, Inc. Tethers Unlimited, Inc.'s mission is to develop advanced propulsion, power, communications, and robotics technologies to provide transformative capability enhancements and dramatic cost savings for applications in space, sea, earth, and air. TUI has expanded its focus and expertise to address technology needs for high-performance components for small satellites, robotic assembly and fabrication technologies, optical fiber winding and deployment, navigation sensors, communications systems, and other advanced technology areas. In addition, TUI specializes in space tethers. A space tether is a long cable used to couple spacecraft to each other or to other masses, such as a spent booster rocket, space station, or an asteroid. Space tethers are usually made of thin strands of high-strength fibers or conducting wires. The tether can provide a mechanical connection between two space objects that enables the transfer of energy and momentum from one object to the other, and as a result they can be used to provide space propulsion without consuming propellant. Additionally, conductive space tethers can interact with the Earth's magnetic field and ionospheric plasma to generate thrust or drag forces without expending propellant. [from their website]

Liftport Link humanity from our home, Earth, to our Moon, to our planets, and to the stars; Earn a substantial return on investment for commercially developing advanced technologies; Learn what we need to learn, to build Elevators to and in space – and build them!; Commercialize mass-cargo cislunar space transportation; Changing the world – improving it – is worth the effort. Building something great requires the best we have to offer; People matter; Integrity and Global Teamwork matter; and, accountability, for generations, to their global stakeholders. Earn a substantial return on investment for commercially developing advanced technologies; Learn what we need to learn, to build Elevators to and in space – and build them!; and, Commercialize mass-cargo cislunar space transportation. [from their website]

2.3 INVESTMENT Sponsors:

Investment in these companies by members of the Forbes Billionaire list is becoming increasingly fashionable. The list of six space-investing Billionaires in 2011[Messier, 2011] has grown to ten in 2013 with a combined net worth of over $106 Billion Dollars as shown in Table 2.1 below. Compare that to the estimated 2013 NASA budget of $17.8 Billion US Dollars.

rank	name	age	net worth	source	space investment
19	Jeff Bezos	49	$25.20	Amazon	Blue Origin
21	Sergey Brin	40	$22.80	Google	Google Lunar X Prize
20	Larry Page	40	$23.00	Google	Google Lunar X Prize, Planetary Resources
53	Paul Allen	60	$15.00	Microsoft	SpaceShipOne, SETI telescope array
138	Eric Schmidt	58	$8.20	Google	Planetary Resources
272	Sir Richard Branson	63	$4.60	Virgin Group	Virgin Galactic
527	Elon Musk	42	$2.70	PayPal, Tesla Motors	SpaceX
831	Guy Laliberte	53	$1.80	Cirque du Soleil	Visitor to ISS
922	K Ram Shriram	56	$1.65	Google	Planetary Resources
1031	Ross Perot, Jr.	54	$1.40	Oil & Gas	Planetary Resources
			$106.35	**Total Net Worth**	

Table 2-1, Billionaire space investors in 2013[Forbes, 2013]

The list of high net-worth individuals investing in space also includes Robert Bigelow (Bigelow Aerospace), Charles Simonyi (Planetary Resources), Richard Garriott (Visitor to ISS), Mark Shuttleworth (Visitor to ISS), Anousheh Ansari (X-Prize), Dennis Tito (Inspiration Mars), Bas Lansdorp (Mars One), Naveen Jain (Moon Express), Barney Pell (Moon Express), Tom Pickens (SpaceHab) and John Carmack (Armadillo Aerospace). The cumulative wealth of private space investors continues to grow.

Information regarding commercial design reference missions remains sparse. This is partly due to the proprietary and confidential nature of trade secrets; however, information is steadily making its way into the public domain. Mars-bound settlers will no doubt benefit from, and indeed even form a robust market for, SMR-derived propellants. Recent announcements by SpaceX founder Elon Musk of his desire to build an 80,000-strong Mars colony within his lifetime carry significant weight. The number of people who have already signed up for Bas Lansdorp's Mars One one-way mission has already exceeded 200,000 people demonstrating that risk preferences for human Mars exploration are loosening [Wong, 2013].

2.4 Applicable Government Project – Asteroid Re-Direct

Across the international arena, there are many plans to take humans beyond low Earth orbit. Each individual country has a hope of increasing its prestige within its own populous as well as its standing with world governments. Many have stated that they are going to place people on the Moon and Mars in the long run. Each program has its strengths and game plan with a schedule for implementation and a technological plan to prepare the hardware. However, there is one plan that is a direct parallel to the plans of the commercial SMR companies. NASA has implemented, and is well along the way towards planning, its Asteroid Re-Direct program. Its plan is to robotically go to an asteroid, that is near Earth, and move it from its natural orbit to a Low Lunar orbit. This will then enable NASA to exercise its human program with a rendezvous by a government sponsored vehicle such as the Orion Capsule for studying the asteroid as well as mining it for samples to return to the Earth. Their program is described below:

> "NASA is on the hunt for an asteroid to capture with a robotic spacecraft, redirect to a stable orbit around the moon, and send astronauts to study in the 2020s -- all on the agency's human Path to Mars. Agency officials announced on Thursday recent progress to identify candidate asteroids for its Asteroid Redirect Mission (ARM), increase public participation in the search for asteroids, and advance the mission's design. NASA plans to launch the ARM robotic spacecraft in 2019 and will make a final choice of the asteroid for the mission about a year before the spacecraft launches. NASA is working on two concepts for the mission: the first is to fully capture a very small asteroid in open space, and the second is to collect a boulder-sized sample off of a much larger asteroid. The agency will choose between these two concepts in late 2014 and further refine the mission's design. NASA's Spitzer Space Telescope made recent observations of an asteroid, designated 2011 MD, which bears the characteristics of a good candidate for the full capture concept. While NASA will continue to look for other candidate asteroids during the next few years as the mission develops, astronomers are making progress to find suitable candidate asteroids for humanity's next destination into the solar system." [www.nasa.gov] This conceptual image shows NASA's Orion spacecraft approaching the robotic asteroid capture vehicle. The trip from Earth to the captured asteroid will take Orion and its two-person crew an estimated nine days."[NASA, 2014]

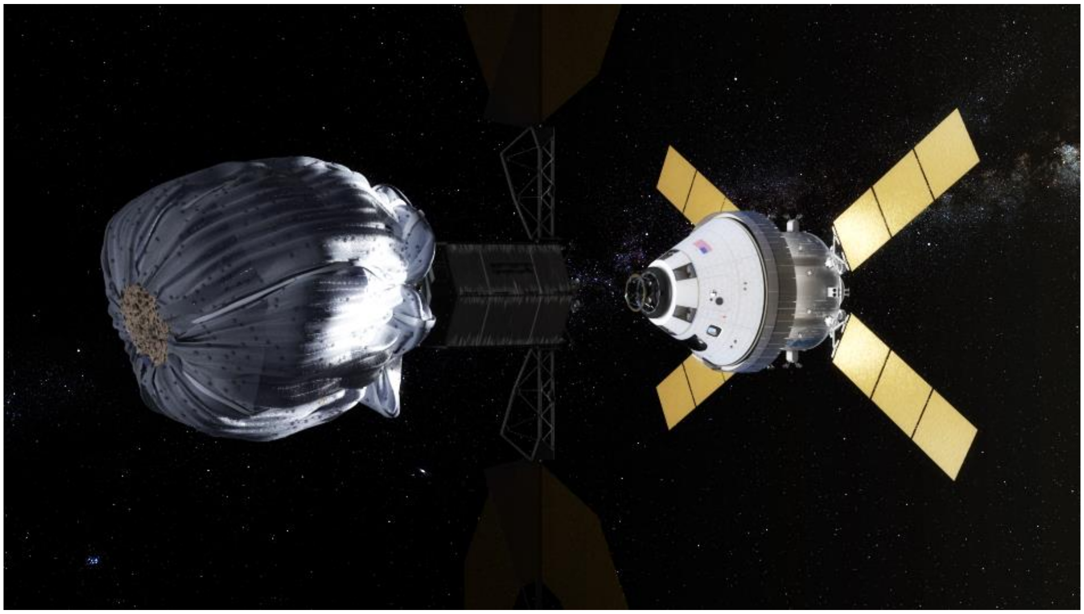


Figure 2-3, Orion Docking Approach [NASA image]

One of the major benefits to the SMR community from this significant NASA initiative is the ability to leverage all of their NEA databases. Just recently, NASA has set up a classification approach to identify NEAs which are to meet their needs with their ability to match locations, approach/investigate, "walk" on the surface, and move it back to LLO. In June 2014, NASA has three NEAs that can be approached and brought back to the lunar area. This identification and classification of NEAs will also greatly enable commercial asteroid mining efforts. In addition, NASA awarded 18 contracts to conduct research into the Asteroid Initiative, for $ 4.9 million over six months. The following research projects have direct applicability to the SMR plans for asteroids.

	Asteroid capture system	
Asteroid Capture System	Airborne Systems North America	will fabricate and test a proof-of-concept inflatable capture system
Asteroid Capture System Conceptual Study	Jacobs, Houston	will test a subscale capture system using mechanically deployed booms.
Kraken Asteroid Boulder Retrieval System	Altius Space Machines	will test prototype grasping arms and innovative gripper concepts for capturing a boulder off the surface of an asteroid
Autonomous Boulder Liberation Equipment	Space Systems/Loral	will demonstrate robotic arms for placement and handling of pneumatic excavation tools, boulder jacking devices, and positive capture

		and restraint tools
	Rendezvous sensors	
Rendezvous Sensor Suite Development	Ball Aerospace and Technologies Corp.	to upgrade a visible camera and LIDAR developed for Orion to meet Asteroid Redirect Mission automated rendezvous and docking requirements
Asteroid Redirect Mission Rendezvous Sensors	The Boeing Company	activity leverages existing visible and infrared sensors and a 3D LIDAR to meet Asteroid Redirect Mission automated rendezvous and docking requirements
	Adapt commercial spacecraft	
Adapting Commercial Spacecraft for the Asteroid Redirect Vehicle	Lockheed Martin Space Systems Company	will define system concepts for a Solar Electric Propulsion Module based on an existing commercial spacecraft bus and NASA Hall thrusters
Multipurpose SEP Module for ARM and Beyond	ExoTerra Resource	will define concepts for an extensible multipurpose Solar Electric Propulsion module designed for launch on Falcon 9.
Adapting Commercial Spacecraft for the Asteroid Redirect Vehicle	The Boeing Company	will define and analyze variants of an existing commercial spacecraft with NASA-furnished solar arrays and Hall thrusters
Adapting Commercial Spacecraft for the Asteroid Redirect Vehicle	Space Systems/Loral	will define system concepts that leverage an existing high-power commercial satellite bus to reduce costs
	Partnerships for secondary payloads	
LIFE on ARM: Accommodating the Living Interplanetary Flight Experiment (LIFE) on the Asteroid Redirect Mission (ARM)	The Planetary Society	whose small passive payload on the Asteroid Retrieval Vehicle would transport extremophiles through deep space and return them to Earth to test panspermia and astrobiology
Arkyd Spacecraft Collaboration with NASA’s Asteroid Initiative	Planetary Resources Development Corp	will determine how three classes of small, low-cost spacecraft being developed by Planetary Resources could be modified to enhance NASA’s planned asteroid missions
Planetary Object Geophysical Observer (POGO)	Johns Hopkins Applied Physics Laboratory	a secondary payload that is a hopper to be dropped on the asteroid surface by the Asteroid Retrieval Vehicle to measure elemental composition of asteroid regolith at multiple locations
Shotgun	Honeybee Robotics Spacecraft Mechanisms Corp	a secondary payload that would deploy multiple small kinetic impactors from the Asteroid Retrieval Vehicle to characterize asteroid regolith
Secondary Spacecraft in Support of ARM	Deep Space Industries	will assess three spacecraft types being developed by DSI for compatibility with the ARV or launch on SLS, and examine public-private partnership approaches
	Address potential partnerships for U.S. exploration activities in cis-lunar space with	

	the crewed mission	
NanoDrill and Caching System	Honeybee Robotics Spacecraft Mechanisms Corp	will develop concepts for drilling tools and sample caching systems that could be used by astronauts during a spacewalk on the asteroid
Industry Funded Participation in the Asteroid Initiative	Deep Space Industries	will analyze the economic fundamentals of a commercially oriented Asteroid Initiative and develop figures of merit that are relevant to commercial needs. Potential demonstrations of in-situ resource utilization will also be assessed

Table 2.2, NASA Awarded Research on Asteroid Initiative [NASA, 2014]

In addition, there is one aspect of this Asteroid Redirect Mission that ties together the government and commercial goals. The intention of NASA's ARM is to: "pursue a target of opportunity that benefits scientific and partnership interests, expanding our knowledge of small celestial bodies and enabling the mining of asteroid resources for commercial and exploration needs." [NASA, 2014]

2.5 Benefits of SMRs

Opening the resources of space will not only change our lives, it will change our destiny. Everyone wants to live in a sustainable economy with a high standard of living. To do so, we must intelligently utilize resources, avoid waste, and prioritize the development of space mineral resources, space solar power and the development of high capacity, inexpensive, access to and from deep space. Humanity thrives upon the consumption of mineral resources. Use of future space mineral resources could remove chemical and thermal waste products from the Earth's environment and finance the development of human civilization across the solar system. Their peaceful development could provide both material benefits and spiritual challenges for our developing planetary civilization. Today, humanity spends about $300 billion USD, less than one half of one percent of world GDP, on all space activities. This figure must be kept in mind as we begin consideration of the economic situation in deep space. To put these Earth centered numbers into perspective, we need to look at the value of resources outside of Earth's orbits. Generally, metal rich asteroids have a range of compositions; but, they are mostly iron and nickel. For this reason they are often referred to as ‘nickel irons.’ However the amount of platinum in these metallic asteroids is often over 100 times greater than in platinum ore on Earth. A look at mineral distribution within asteroids is shown in the next chart.

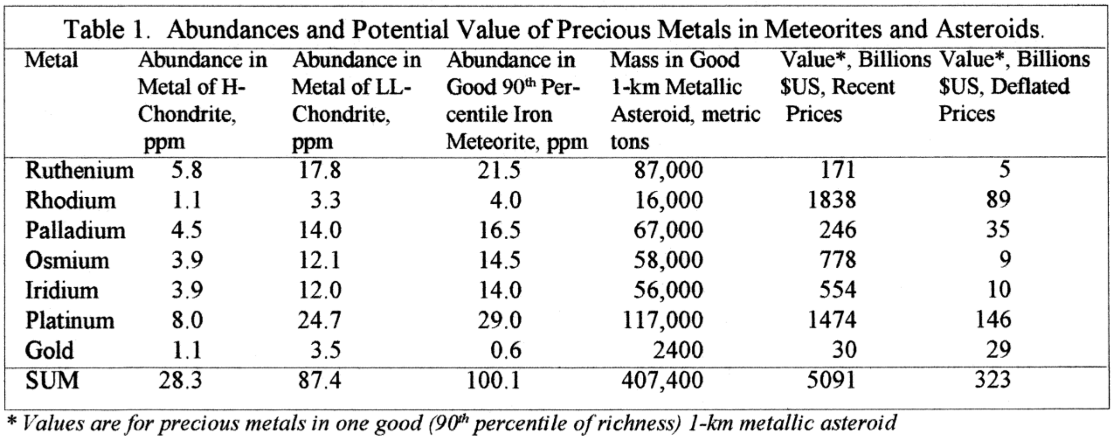


Table 1. Abundances and Potential Value of Precious Metals in Meteorites and Asteroids.

Metal	Abundance in Metal of H-Chondrite, ppm	Abundance in Metal of LL-Chondrite, ppm	Abundance in Good 90th Percentile Iron Meteorite, ppm	Mass in Good 1-km Metallic Asteroid, metric tons	Value*, Billions $US, Recent Prices	Value*, Billions $US, Deflated Prices
Ruthenium	5.8	17.8	21.5	87,000	171	5
Rhodium	1.1	3.3	4.0	16,000	1838	89
Palladium	4.5	14.0	16.5	67,000	246	35
Osmium	3.9	12.1	14.5	58,000	778	9
Iridium	3.9	12.0	14.0	56,000	554	10
Platinum	8.0	24.7	29.0	117,000	1474	146
Gold	1.1	3.5	0.6	2400	30	29
SUM	28.3	87.4	100.1	407,400	5091	323

** Values are for precious metals in one good (90th percentile of richness) 1-km metallic asteroid*

Figure 2-4, Precious Metal Abundances for
LL Chondrites and Iron Asteroids. [Kargel, 1994]

It is reasonable to say that the basic parametrics of Space Mineral Resources (SMR) are not yet widely understood by political decision makers. This study is meant to remedy that. Every raw material found on Earth, without exception, can be found in space in vastly greater quantities. Clearly, space offers vast inventories of mineral wealth. The next question becomes which space resources are amenable to near-term use? This is a matter of utility; and therefore, defines the payoff for investment in SMR.

> “The purpose of In-Situ Resource Utilization (ISRU), or “living off the land,” is to harness and utilize space resources to create products and services which enable and significantly reduce the mass, cost, and risk of near-term and long-term space exploration. ISRU can be the key to implementing a sustained and affordable human and robotic program to explore the solar system and beyond. Potential space resources include water, solar wind implanted volatiles (hydrogen, helium, carbon, nitrogen, etc.), vast quantities of metals and minerals, atmospheric constituents, unlimited solar energy, regions of permanent light and darkness,

> the vacuum and zero-gravity of space itself, and even trash and waste from human crew activities. Suitable processing can transform these raw resources into useful materials and products.” [Sanders, 2005]

The benefits of using space mineral resources (SMR) are reduced cost, increased capability and autonomy, and the generation of economic profit. As costs fall, more resources can be harvested. As more resources are harvested, humanity will solidify its foothold in space. SMR utilization essentially creates a feedback loop that will exponentially increase our access to space.

The most valuable near Earth asteroids (NEAs) are those whose orbits closely mimic that of Earth, so that minimal energy is required to reach them and return. NEAs are a plentiful resource (currently > 2 million NEAs estimated) and the availability of affordable-to-reach targets will continue to expand. Every month a NEA with the potential to end civilization (one km or larger) is discovered. The chart [Figure 2-5] below shows the numbers of NEAs discovered during each of the last 30 years. More emphasis by NASA [and other agencies] have increased the rate of discovery.

Technical information related to Space Mineral Resources disclosed in this report include published NASA and international space agency technology roadmaps, TRL (technology readiness level) estimates, architectural options, common and unique systems elements, and recommended investment paths. Policy information summarizes the current international legal environment, and steps that could be taken to accelerate resource development, including recommendations for removing roadblocks. Economic analysis casts SMR into a framework or context for understanding the basis for present and future value to public and private stakeholders, and includes an assessment of the influence of current and projected policy on economics. The near term roadmap will naturally fall within the CisLunar Econosphere, as shown in Figure 2-6.

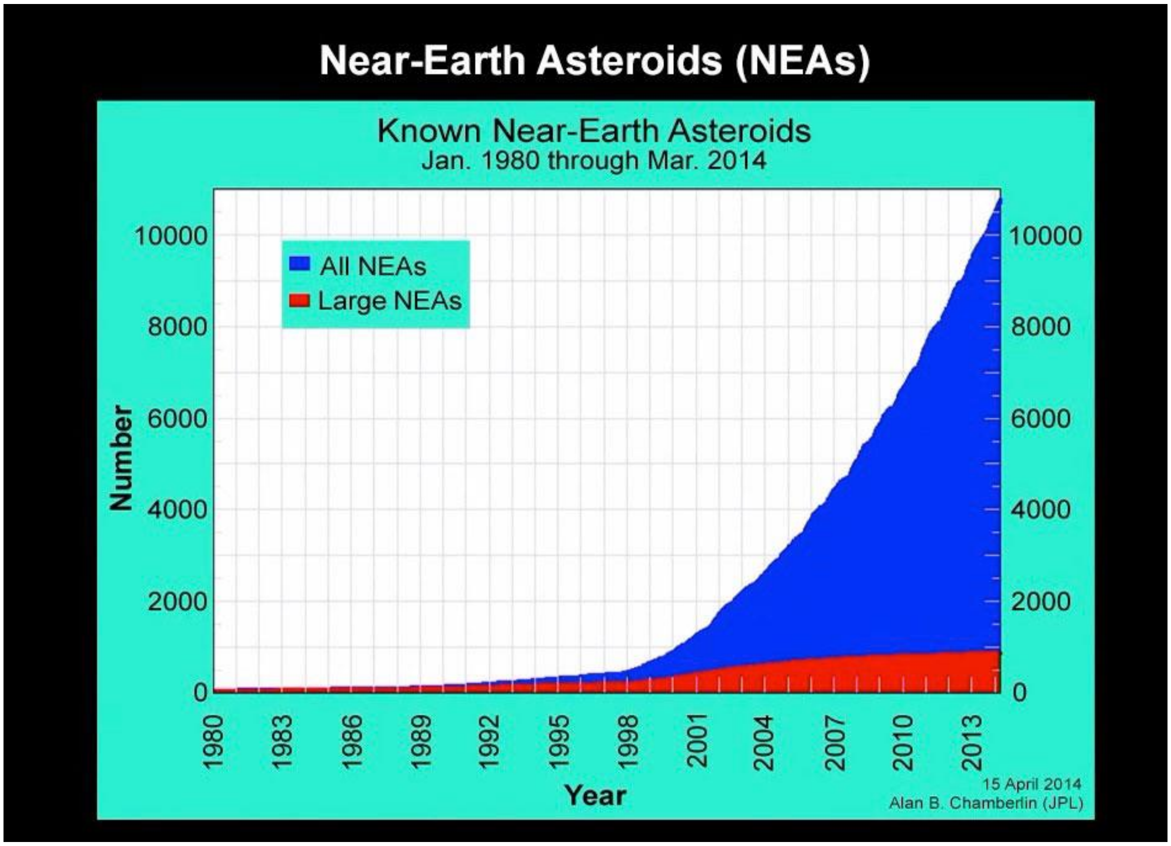
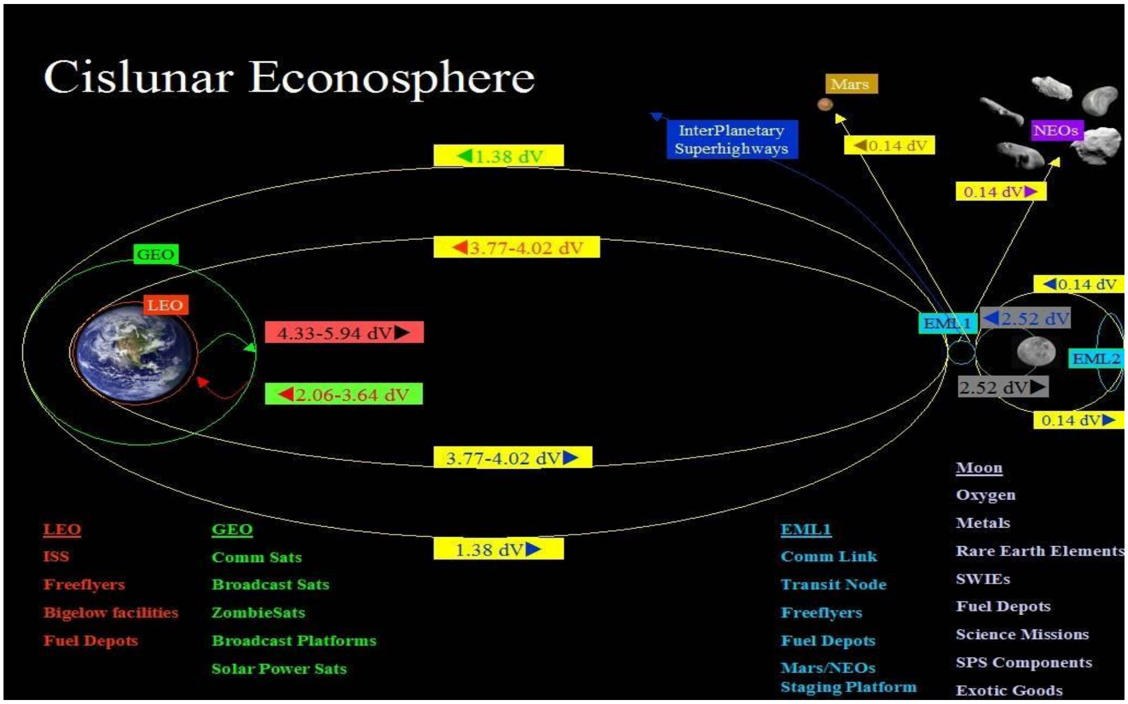


Figure 2-5, Known NEAs [Chamberlin, 2014]



Cislunar Econosphere

LEO
ISS
Freeflyers
Bigelow facilities
Fuel Depots

GEO
Comm Sats
Broadcast Sats
ZombieSats
Broadcast Platforms
Solar Power Sats

EML1
Comm Link
Transit Node
Freeflyers
Fuel Depots
Mars/NEOs Staging Platform

Moon
Oxygen
Metals
Rare Earth Elements
SWIEs
Fuel Depots
Science Missions
SPS Components
Exotic Goods

Figure 2-6. Cislunar Econosphere showing

Delta-V and Products. [Murphy, 2012]

2.6 Mining SMRs

A wide array of mining and mineral extraction technologies exist today. Because of the similarity between space and terrestrial resources, much of this technology should readily adapt to the unique environmental physics of the Moon, Mars and asteroids. Nearly 50 years worth of planetary surface missions has yielded extensive data showing the mineral inventory of space resources as well as collecting data on the unique environmental context of future ore bodies. This rich data set has generated a large pool of thought for adapting traditional methods of mineral extraction and refining to the unforgiving conditions of space such as cold, high vacuum, and microgravity. The potential exists for developing and proving novel mining methods that leverage unique environmental factors for actual savings compared to the energy and complexity requirements of current technology. In addition, technologies developed for SMR could offer synergistic benefits to terrestrial mining and mineral processing.

2.6.1 Sunlight Acquisition

The reader must remember that the purpose of commercial space is to make a profit while accomplishing resource exploitation. This fits into the first concept in a spectrum of options: Sell Sunlight! If there were a platform in LEO [or GEO] that would provide stability, for pointing, and electricity, customers would come. This implies that the first embryonic steps of SMR ventures could also provide profit. Most SMR ventures have initial steps that will use telescopes to understand their asteroid targets of opportunity. What if they had a robust facility on orbit with extra solar arrays and maybe even extra fuel? Could they sell those assets at a profit while conducting mission operations to identify and characterize SMR locations such as lunar or NEA surfaces?

2.6.2 Material (Ores) Acquisition

Asteroids: As we begin to map the solar system, we have discovered both immense resources that could be the key to our future prosperity and threats to the survival of, not only our civilization, but our entire species. Both are space mineral resources; specifically the solar system's millions of asteroids orbiting the sun. It is now time for humankind to decide to either use these resources to build a grand and glorious civilization across the solar system and beyond, or to ignore them, stay on Earth, and be destroyed, sooner or later, by asteroid impacts. This report deals with utilization of space mineral resources, but is aware of the NEO activities and the protection of Earth from asteroids programs. Remember the dinosaurs did not have a space program. Our choice, as H.G. Wells put it, is "The universe or nothing."

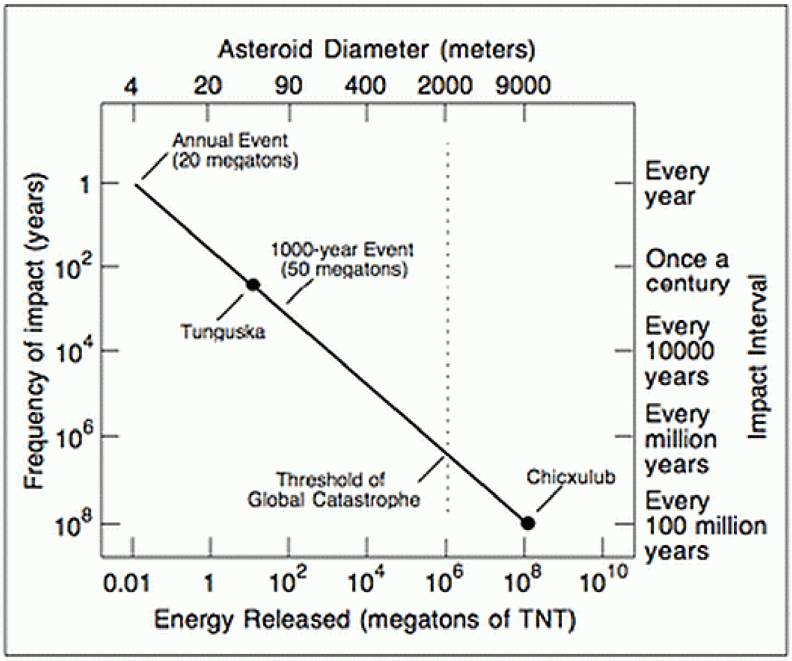


Figure 2-7, Asteroid Size vs. Numbers [NASA image]

We have, within our collective reach, the technological, economic, legal and policy means to measure, then mitigate this threat; and, even turn it into orders of magnitude greater material abundance than was ever conceived. The estimated population capacity of the inner solar system is ten quadrillion humans, assuming middle-class consumption patterns remain in place. Today's economy will scale with that growth, enabling private and commercial enterprises to thrive. Space miners can acquire asteroid ore and process it on site, shipping out only the refined components; or, they could transport raw or beneficiated ore to stable locations near or on Earth for processing. Both approaches may make sense for particular applications in various situations. On-site processing saves transportation costs by shipping only the valuable portion of the NEA. The challenge is that NEAs have low-energy near-Earth approaches infrequently, so the wait between placing processing equipment on an NEA and its next close pass when products can be shipped can be ten, twenty or even fifty years. Many more NEAs and their orbits need to be charted to see if on-site processing can be accomplished in time periods that make economic sense. The next figure is the asteroid Itokawa, which is about one kilometer long and was visited by the Japanese space probe Hayabusa in 2005. A mineral sample from this asteroid was returned to Earth in 2010. This was the first mineral to be mined from an asteroid.

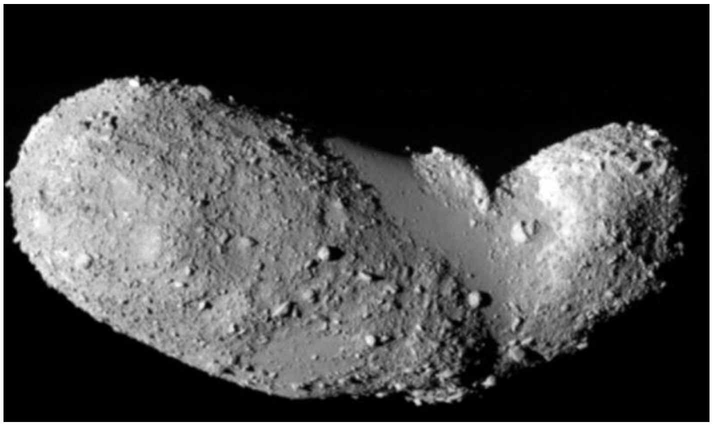


Figure 2-8, Asteroid Itokawa [Itokawa, 2005]

An alternative is to move raw asteroid material into a parking orbit near Earth or directly to Earth, either by moving an entire small NEA (one to ten meters diameter) or by collecting parts of a larger NEA and delivering that subsample. Small NEAs, by their very nature, are difficult to spot from Earth, and hard to acquire and track by spacecraft sent out to find them in the vastness of interplanetary space. Medium NEAs are more plentiful in the existing NEA database, and easier to spot and track by approaching spacecraft. Some, such as asteroid 25143 Itoakawa, are littered with boulders that presumably could be collected and delivered back to an Earth orbit. Others appear relatively smooth and may require some means to acquire a subsample – shearing, shattering or drilling to create a piece of the right size for transport.

A good systems design was accomplished for catching and stabilizing an asteroid by the SETI Institute. They have shared their NASA proposal with a great image and the approach: [NASA, 2014]

> “SHEPHERD is a concept for gentle capture, with no hard surface contact with the asteroid, motivated not only by the science value

of understanding the internal strength, internal structure, response to de-spinning, and surface weathering phenomena of small NEA, but also by the value of delivering an intact asteroid to the Earth-Moon system, rather than a bag of rocks, to make the ARM mission a suitable stepping stone for human spaceflight towards longer duration missions to asteroids in solar orbit, and ultimately Mars."

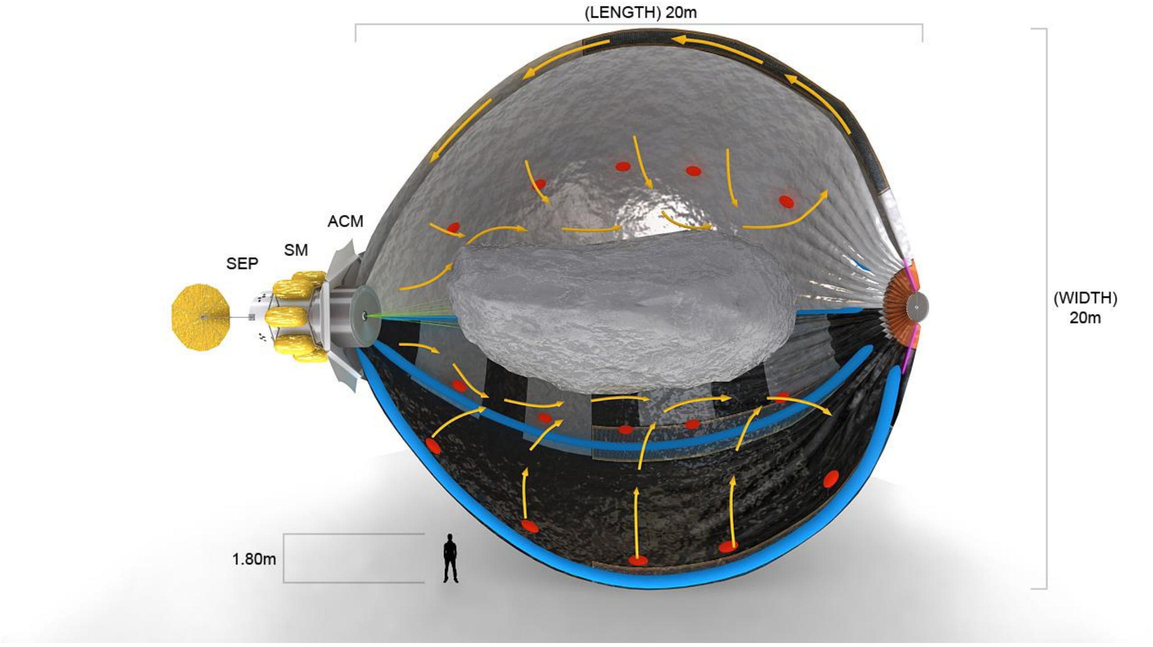


Figure 2-9, The Shepherd Concept [Digital Space & SETI Institute]

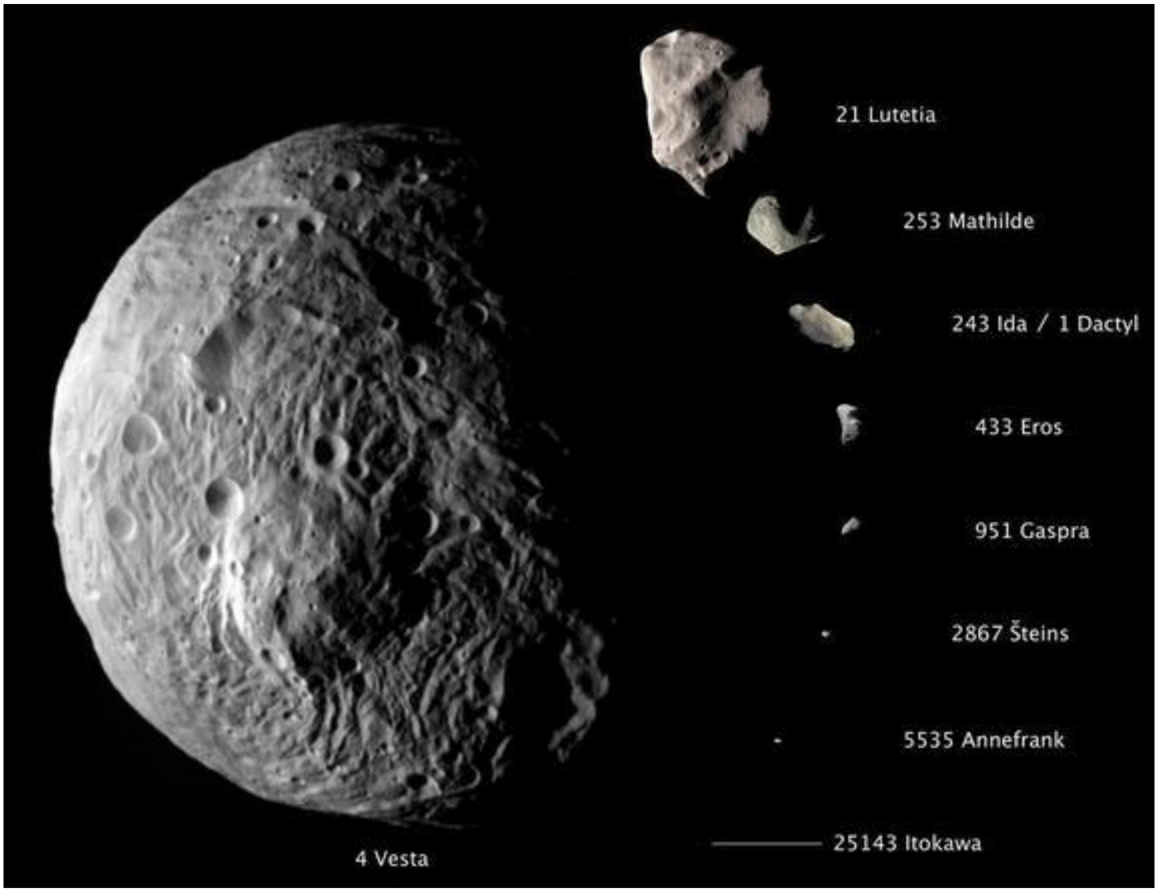


Figure 2-10, Asteroids [Itokawa is small] [NASA image]

Between 1980 and 2013, about 10,000 Near Earth Asteroids were discovered. This is still too many to discuss. They are composed of ice, rock, carbon compounds and metal. This should not be a surprise as the Earth was formed from collisions of billions of these asteroids early in the history of the solar system; so, everything on Earth is also in space as mineral resources.

Human Space Flight Accessible Target NEAs: NASA/JPL has an ongoing study to identify asteroid targets that meet their criteria for “mission accessibility.” These dynamically accessible targets would require minimum time to visit and return to Earth. Recently, the JPL team released the latest number of these preferred targets as 1,346. The below chart shows the discovery rate of these preferred targets as of January 2015.

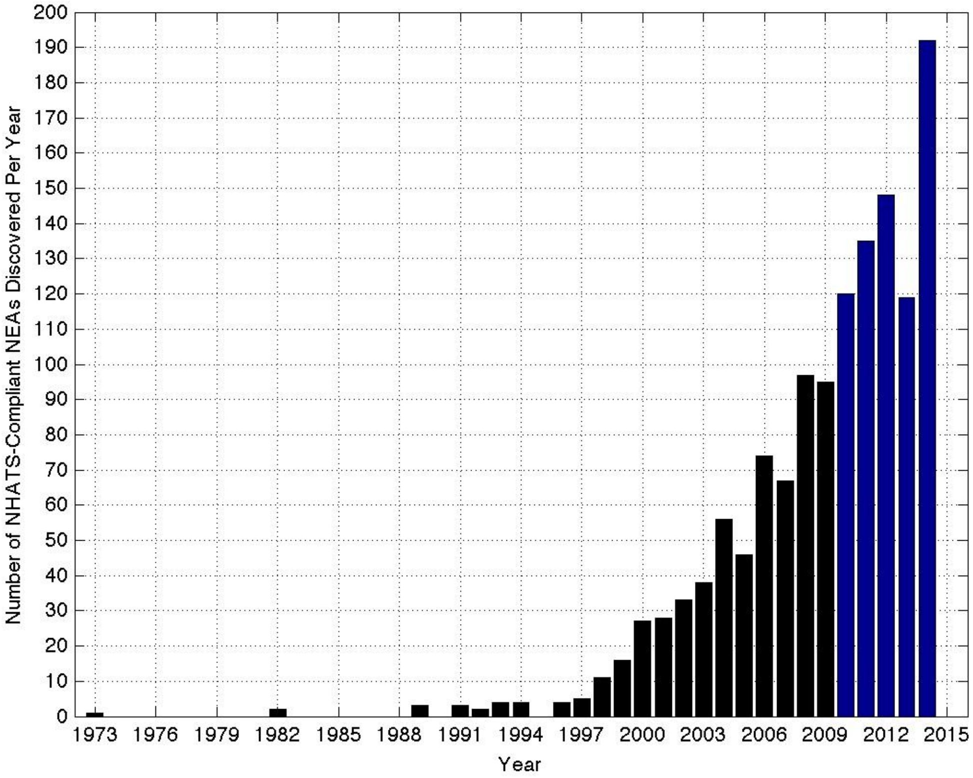
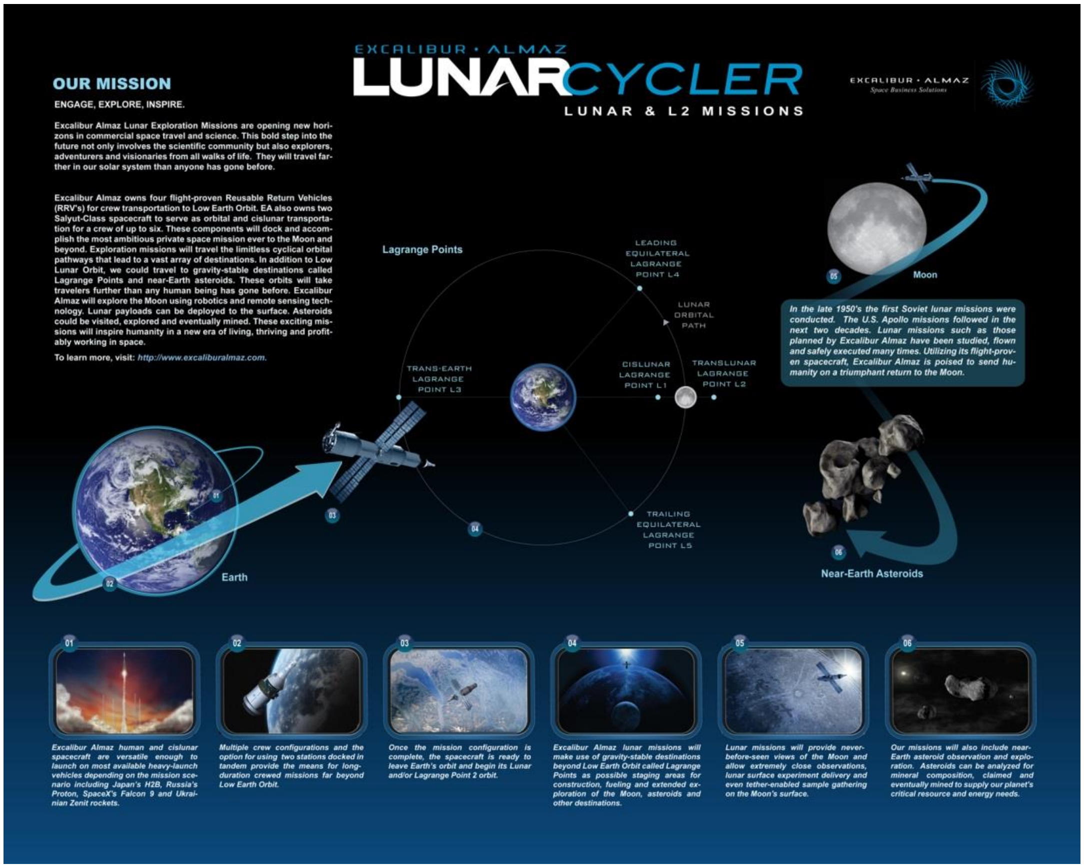


Figure 2-11, Dynamically Accessible NEA Targets
[http://neo.jpl.nasa.gov/news/news189.html]

Planetary: Ore acquisition from the Moon or Mars follows a more traditional formula. The lunar and Mars vision for materials acquisition equipment is extensive, with growing detail on technical features, yet typically converges on the common look of terrestrial mining equipment due to gravity. One important difference is the increase in tractive effort (the pressure equipment needs to exert on the “ground” to create a given forward force) needed for excavation for the Moon vs. Earth. The opposite is true for hauling, which is easier on the Moon as long as momentum effects are not extreme. The next few charts show some concepts to support planetary SMR activities.



EXCALIBUR · ALMAZ

LUNARCYCLER

LUNAR & L2 MISSIONS

EXCALIBUR · ALMAZ
Space Business Solutions

OUR MISSION

ENGAGE, EXPLORE, INSPIRE.

Excalibur Almaz Lunar Exploration Missions are opening new horizons in commercial space travel and science. This bold step into the future not only involves the scientific community but also explorers, adventurers and visionaries from all walks of life. They will travel farther in our solar system than anyone has gone before.

Excalibur Almaz owns four flight-proven Reusable Return Vehicles (RRV's) for crew transportation to Low Earth Orbit. EA also owns two Salyut-Class spacecraft to serve as orbital and cislunar transportation for a crew of up to six. These components will dock and accomplish the most ambitious private space mission ever to the Moon and beyond. Exploration missions will travel the limitless cyclical orbital pathways that lead to a vast array of destinations. In addition to Low Lunar Orbit, we could travel to gravity-stable destinations called Lagrange Points and near-Earth asteroids. These orbits will take travelers further than any human being has gone before. Excalibur Almaz will explore the Moon using robotics and remote sensing technology. Lunar payloads can be deployed to the surface. Asteroids could be visited, explored and eventually mined. These exciting missions will inspire humanity in a new era of living, thriving and profitably working in space.

To learn more, visit: *http://www.excaliburalmaz.com.*

In the late 1950's the first Soviet lunar missions were conducted. The U.S. Apollo missions followed in the next two decades. Lunar missions such as those planned by Excalibur Almaz have been studied, flown and safely executed many times. Utilizing its flight-proven spacecraft, Excalibur Almaz is poised to send humanity on a triumphant return to the Moon.

01 *Excalibur Almaz human and cislunar spacecraft are versatile enough to launch on most available heavy-launch vehicles depending on the mission scenario including Japan's H2B, Russia's Proton, SpaceX's Falcon 9 and Ukrainian Zenit rockets.*

02 *Multiple crew configurations and the option for using two stations docked in tandem provide the means for long-duration crewed missions far beyond Low Earth Orbit.*

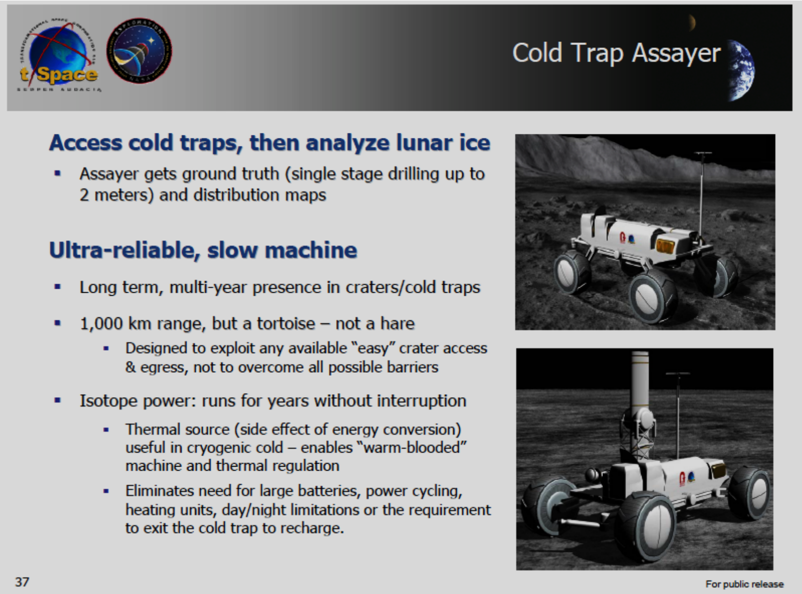
03 *Once the mission configuration is complete, the spacecraft is ready to leave Earth's orbit and begin its Lunar and/or Lagrange Point 2 orbit.*

04 *Excalibur Almaz lunar missions will make use of gravity-stable destinations beyond Low Earth Orbit called Lagrange Points as possible staging areas for construction, fueling and extended exploration of the Moon, asteroids and other destinations.*

05 *Lunar missions will provide never-before-seen views of the Moon and allow extremely close observations, lunar surface experiment delivery and even tether-enabled sample gathering on the Moon's surface.*

06 *Our missions will also include near-Earth asteroid observation and exploration. Asteroids can be analyzed for mineral composition, claimed and eventually mined to supply our planet's critical resource and energy needs.*

Figure 2-12, Lunar Cycler [t-space 2005]



Cold Trap Assayer

Access cold traps, then analyze lunar ice

- Assayer gets ground truth (single stage drilling up to 2 meters) and distribution maps

Ultra-reliable, slow machine

- Long term, multi-year presence in craters/cold traps
- 1,000 km range, but a tortoise – not a hare
  - Designed to exploit any available "easy" crater access & egress, not to overcome all possible barriers
- Isotope power: runs for years without interruption
  - Thermal source (side effect of energy conversion) useful in cryogenic cold – enables "warm-blooded" machine and thermal regulation
  - Eliminates need for large batteries, power cycling, heating units, day/night limitations or the requirement to exit the cold trap to recharge.

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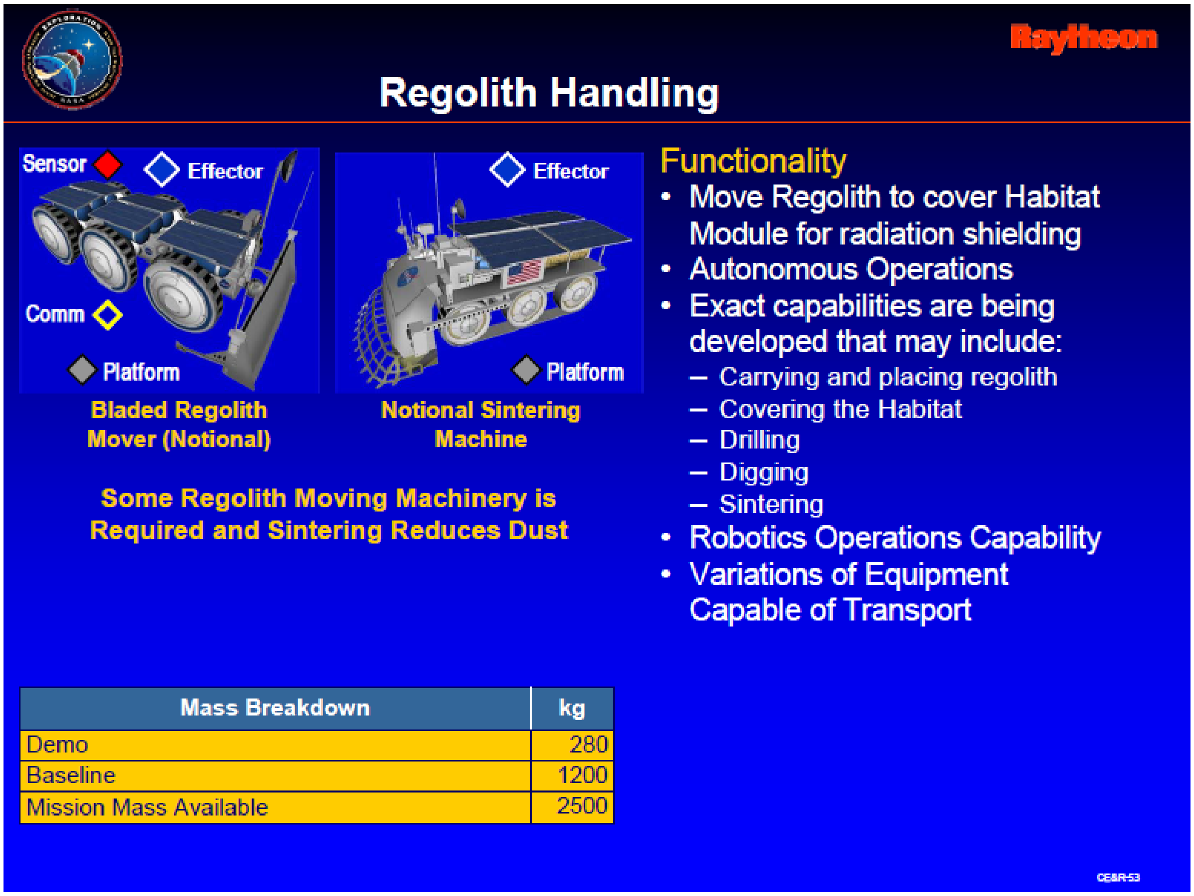
Figure 2-13, Lunar Cold Trap Assay Vehicle [tSpace, 2005].



Raytheon

Regolith Handling

Bladed Regolith Mover (Notional)

Notional Sintering Machine

Some Regolith Moving Machinery is Required and Sintering Reduces Dust

Functionality

- Move Regolith to cover Habitat Module for radiation shielding
- Autonomous Operations
- Exact capabilities are being developed that may include:
  - Carrying and placing regolith
  - Covering the Habitat
  - Drilling
  - Digging
  - Sintering
- Robotics Operations Capability
- Variations of Equipment Capable of Transport

Mass Breakdown	kg
Demo	280
Baseline	1200
Mission Mass Available	2500

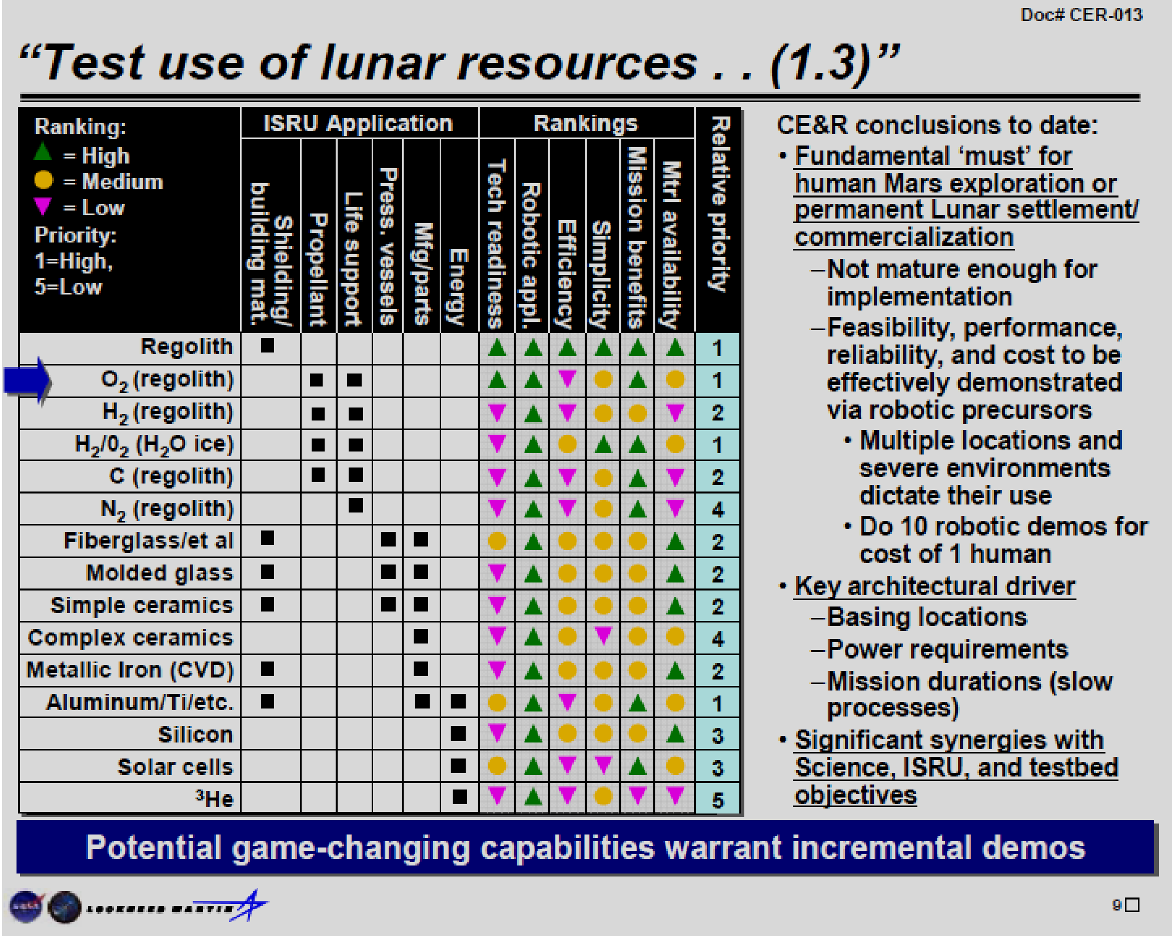
CE&R-53

Figure 2-14. Materials Handling Systems Concept [Raytheon, 2005].

Classes of lunar resources can be divided into the following basic categories:

- Polar ice & mixed volatiles
- Equatorial ilmenite / iron oxide
- Building materials
- Glass & refined metals
- Helium-3

Extensive evaluation of the uses of lunar materials has taken place, as shown in the next chart.



Doc# CER-013

"Test use of lunar resources . . (1.3)"

Ranking:
▲ = High
● = Medium
▼ = Low
Priority:
1=High,
5=Low

	ISRU Application						Rankings						
	Shielding/ building mat.	Propellant	Life support	Press. vessels	Mfg/parts	Energy	Tech readiness	Robotic appl.	Efficiency	Simplicity	Mission benefits	Mtrl availability	Relative priority
Regolith	■						▲	▲	▲	▲	▲	▲	1
O_2 (regolith)		■	■				▲	▲	▼	●	▲	●	1
H_2 (regolith)		■	■				▼	▲	▼	●	●	▼	2
$H_2/0_2$ (H_2O ice)		■	■				▼	▲	●	▲	▲	●	1
C (regolith)		■	■				▼	▲	▼	●	▲	▼	2
N_2 (regolith)			■				▼	▲	▼	●	▲	▼	4
Fiberglass/et al	■			■	■		●	▲	●	●	●	▲	2
Molded glass	■			■	■		▼	▲	●	●	●	▲	2
Simple ceramics	■			■	■		▼	▲	●	●	●	▲	2
Complex ceramics					■		▼	▲	●	▼	●	●	4
Metallic Iron (CVD)	■				■		▼	▲	●	●	●	▲	2
Aluminum/Ti/etc.	■				■	■	●	▲	▼	●	▲	●	1
Silicon						■	▼	▲	●	●	●	▲	3
Solar cells						■	●	▲	▼	▼	▲	●	3
^{3}He						■	▼	▲	▼	●	▼	▼	5

CE&R conclusions to date:
- Fundamental 'must' for human Mars exploration or permanent Lunar settlement/ commercialization
  - –Not mature enough for implementation
  - –Feasibility, performance, reliability, and cost to be effectively demonstrated via robotic precursors
    - Multiple locations and severe environments dictate their use
    - Do 10 robotic demos for cost of 1 human
- Key architectural driver
  - –Basing locations
  - –Power requirements
  - –Mission durations (slow processes)
- Significant synergies with Science, ISRU, and testbed objectives

Potential game-changing capabilities warrant incremental demos

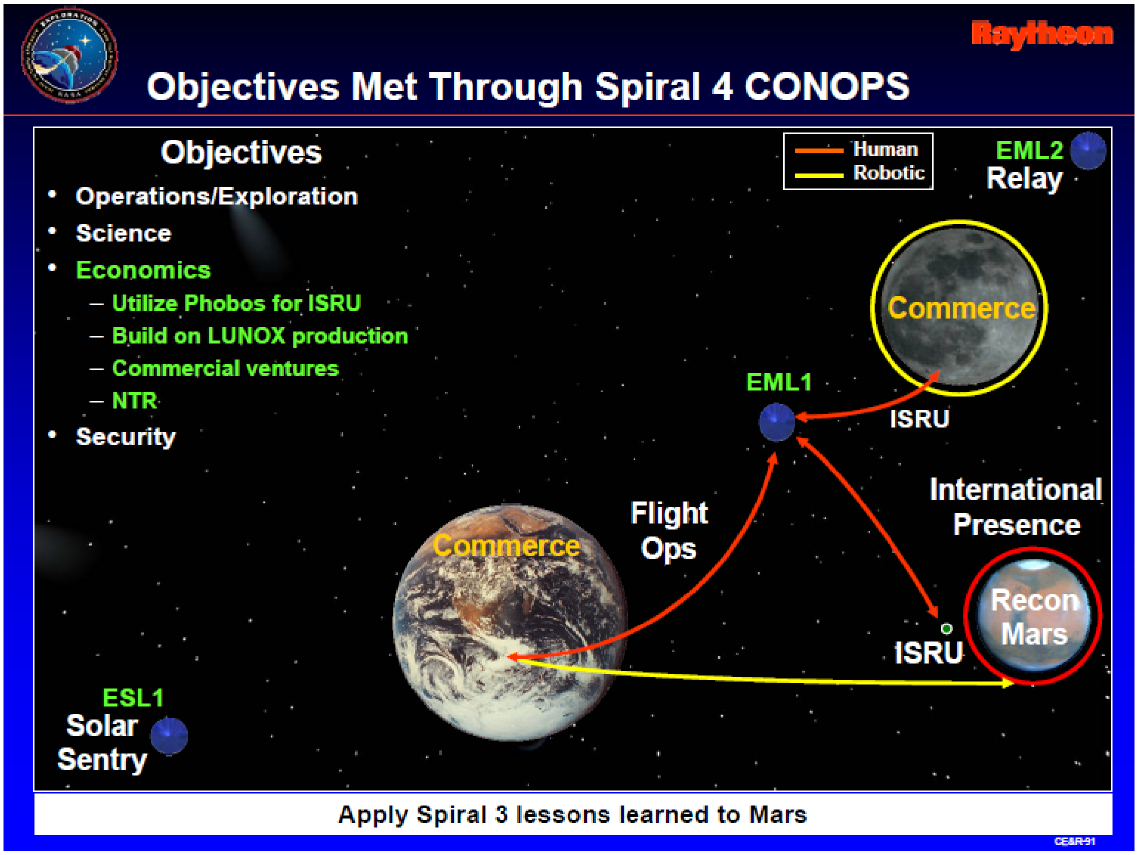
9

Figure 2-15, Lockheed-Martin Evaluation of Lunar SMR Types [Lockheed, 2005].

Due to a growing number of orbiting and surface missions, much has been learned in the last decade about the geology of Mars. Similar to the Moon, there is not enough space in this report to cover the vast details learned; however, relevant resources of Mars that could be used for SMR include:

- Water at poles and in soils
- Gypsum and hydrated soils
- Carbon Dioxide atmospheric processing of methane fuels
- In-situ building materials & greenhouse soils

Note that the Martian moons Phobos and Deimos are typically considered asteroids due to small size (thus very low gravity and the need to "dock" rather than "land") as well as composition. Due to their location, they have frequently been considered as natural space stations for human Mars operations, as shown in next figure.



Objectives Met Through Spiral 4 CONOPS

Objectives

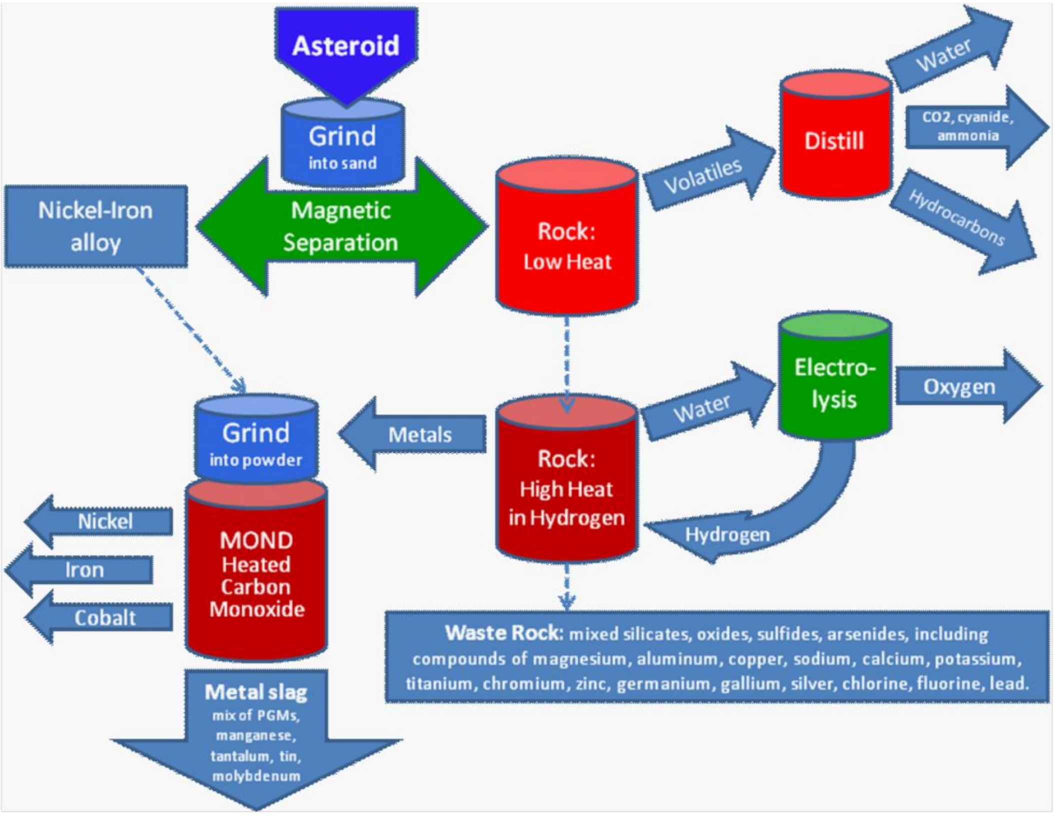
- Operations/Exploration
- Science
- Economics
  - Utilize Phobos for ISRU
  - Build on LUNOX production
  - Commercial ventures
  - NTR
- Security

Apply Spiral 3 lessons learned to Mars

Figure 2-16, Phobos SMR Facilitates [Raytheon, 2005].

2.7 Processing (Ores In, Products Out)

The two primary materials of value expected from asteroids are volatiles and nickel-iron mixtures. Volatiles will be comprised of many elements and compounds (water, ammonia, carbon monoxide and kerogen are expected to be abundant). In addition to nickel-iron (natural stainless steel), much smaller amounts of precious metals are expected. Asteroid processing will likely begin with a subset of processing steps shown below to extract the elements or compounds with the highest immediate value. The residue of these initial processes may be stored until demand for them increases, or less-expensive ways to unlock them are perfected. Material left over after the majority is processed into high-value products still has value for the in-space market as radiation shielding.



Asteroid processing overview – initial asteroid resource production will focus on producing volatiles and selected metals for in-space markets. Slag and waste produced will be sold as radiation shielding.

Source: Deep Space Industries Inc.

Figure 2-17, Asteroid Material Processing (Deep Space Industries).

The circuit above could also extract metal from lunar soil, given the eons of bombardment of asteroidal materials onto the Moon. In addition, processes could extract metal from lunar soil, given the eons of bomasteroidal composition. Lunar polar volatile processing would follow a similar, yet somewhat simpler process, using condensers to capture water vapor for refining and later product delivery. Condensation of water vapor could be done using either pumps (for sealed systems) or cold plates (for open systems). Other lunar polar volatiles of interest such as NH3 (a source of the atmospheric conditioner N2) could also be captured this way.

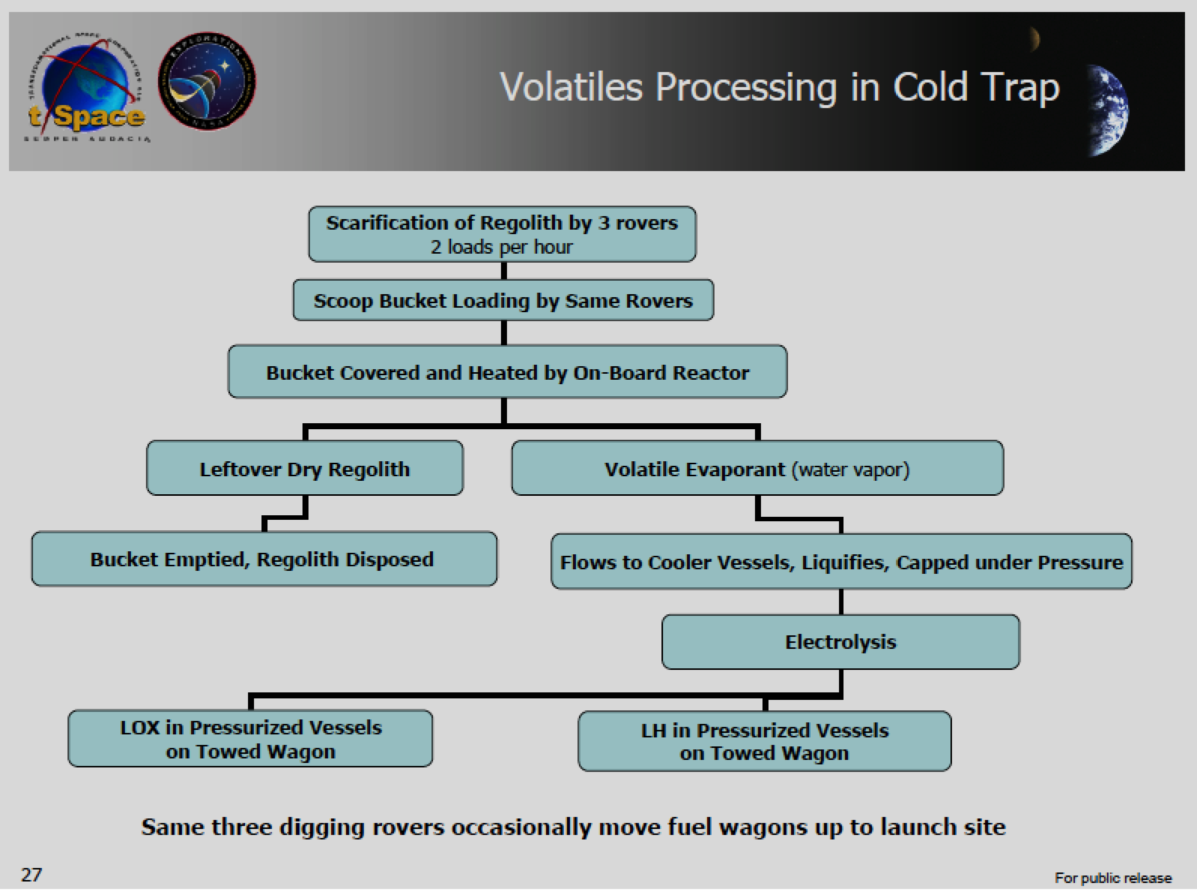
2.8 In-Space Resources and Manufacturing to Support SMR

This section summarizes SMR mining, extraction & refining technology and estimation methods. As stated in numerous sections above, much of terrestrial mining & mineral processing experience can directly apply to SMR. Indeed, gaining the attention of the mining industry offers the potential for significant leverage to public and private SMR initiatives. The physics of space may be somewhat different, requiring a bit of thinking, designing and planning; but, many of the fundamental parameters are the same as on Earth. It takes the same amount of energy to separate oxygen chemically bound to Iron no matter where it happens. Space mineral resource mining and processing unit operations are modular in nature, lending themselves to categorization and simplifying architectural development to a process of combining elemental modules. Modular SMR systems include:

water extractors
PGM extractors
iron and nickel refining separation & printing systems
transportation (both human & cargo) systems
power system options
comm/navigation modules

2.8.1 At-Source Processes

Mineral processing starts with excavation – the separation of a geologic material from its parent body through mechanical or other means. Beneficiation is the name given by extractive industries for electromagnetic separation, screening or sorting processes that happen on the front end – nearest to the excavator. Other processes such as crushing or packaging for transport may find energy savings by being located near the excavation system. Note that this section is a summary of options. An example of a mineral processing circuit starting with scarification and bucket loading.



Volatiles Processing in Cold Trap

Scarification of Regolith by 3 rovers
2 loads per hour

Scoop Bucket Loading by Same Rovers

Bucket Covered and Heated by On-Board Reactor

Leftover Dry Regolith

Volatile Evaporant (water vapor)

Bucket Emptied, Regolith Disposed

Flows to Cooler Vessels, Liquifies, Capped under Pressure

Electrolysis

LOX in Pressurized Vessels
on Towed Wagon

LH in Pressurized Vessels
on Towed Wagon

Same three digging rovers occasionally move fuel wagons up to launch site

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Figure 2-18, SMR Process Flow [t-Space, 2005].

2.8.2 At-Factory Processes

A wide variety of chemical processes have been proposed to extract and refine SMRs into useful products. The list below is a partial summary of some of the options. In prior studies, Gibbs Free Energy has been used as a proxy to estimate production power for various elements or elemental combinations.

- Candidate Unit Processes for SMR
- Material Handling (Includes Storage Prior to Processing)
- Crushing or other Particle Size Reduction
- Devolatilization (typically heating induced)
- Volatiles Distillation / Refining & Separation
- Metals Extraction & Refining
- Silicates & Rock Processing
- Product-Specific Modules

- Life-Support Products (Oxygen, Water, CO2, Nitrogen, Fertilizers, Food)
- Rocket Fuels & Oxidizers
- Polymers
- Glass Products (windows, etc.)
- Glass Fiber Products (Composites/Ropes/Fabrics/Insulation)
- Heat Shields
- Radiation Shields
- Foamed Metal Products
- Semiconductors
- Solar Cells / Panels
- Steel Products (Sheet/Plate/Beams/Rods/Pipes/Fittings/etc.)

2.8.3 SPS Processing

Once again, the concept of selling sunlight seems like a potential commercial business. The primary supporting role Space Systems Power (SSP) can provide to SMR is the provision of low-cost, high density power for industrial operations. The natural segregation of enterprises based upon function is healthy for a robust space settlement initiative. With a growing ecosystem of commercial entities that view each other as customers, there is a built-in natural resistance to systemic collapse. SMR offers SSP a significant benefit as well – a high-priced premium market for its product – power. One of the primary problems with SSP is the cost of launching so much mass into orbit. Hybrid designs that take advantage of SMR for construction of SSP offer win-win partnerships where SSP and SMR become each other's customer.

> "The energy required to accelerate objects into orbit is enormous. The real energy density of sunlight is low. For SSP to make a significant contribution to global energy demands therefore requires an extraordinarily large structure. Large structures require a lot of mass, and a lot of assembly time. These factors are driving a number of research efforts, such as: ultra-thin solar arrays; ultra-lightweight deployable structures; robotic assembly; lunar or asteroid processing; and space elevators. From a systems perspective, the energy required to build, orbit, and assemble huge solar arrays

should be significantly less than the energy delivered to earth." [Schubert, 2010]

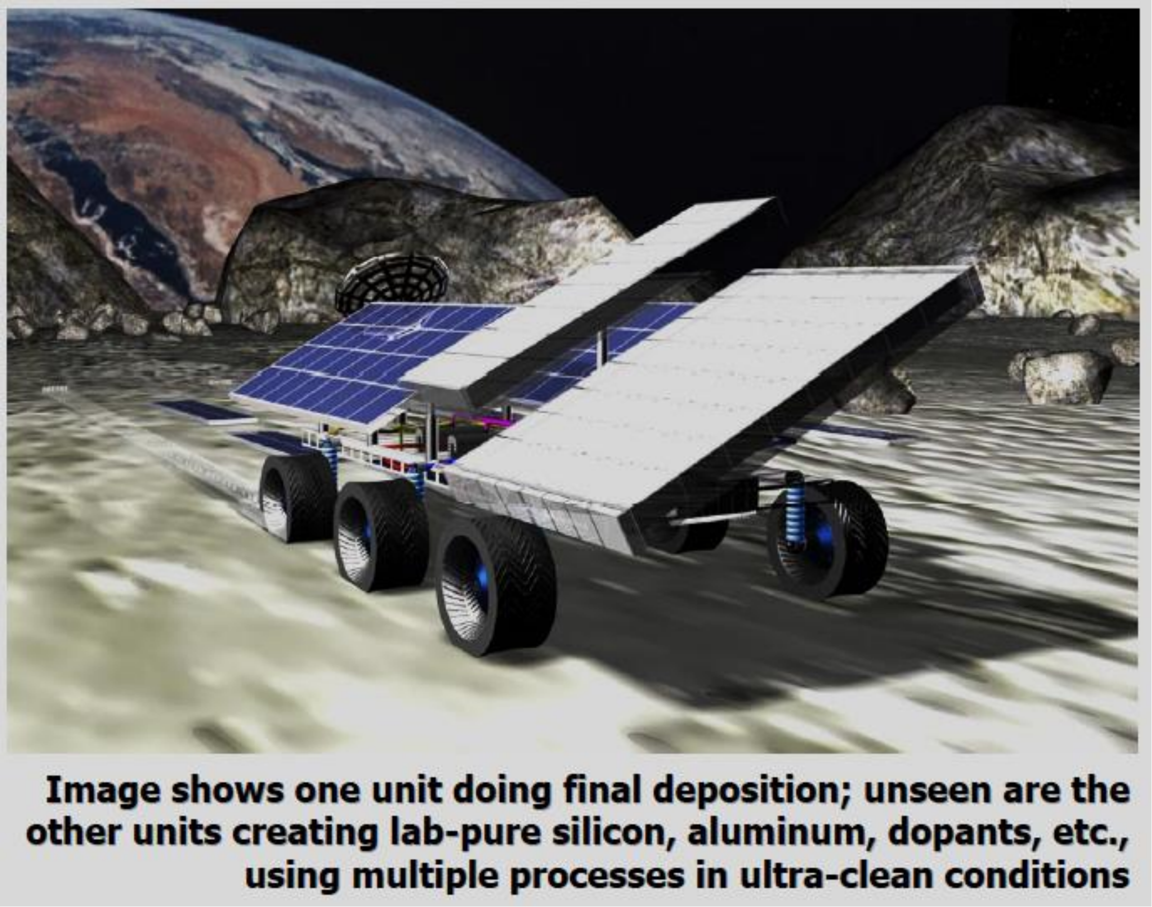


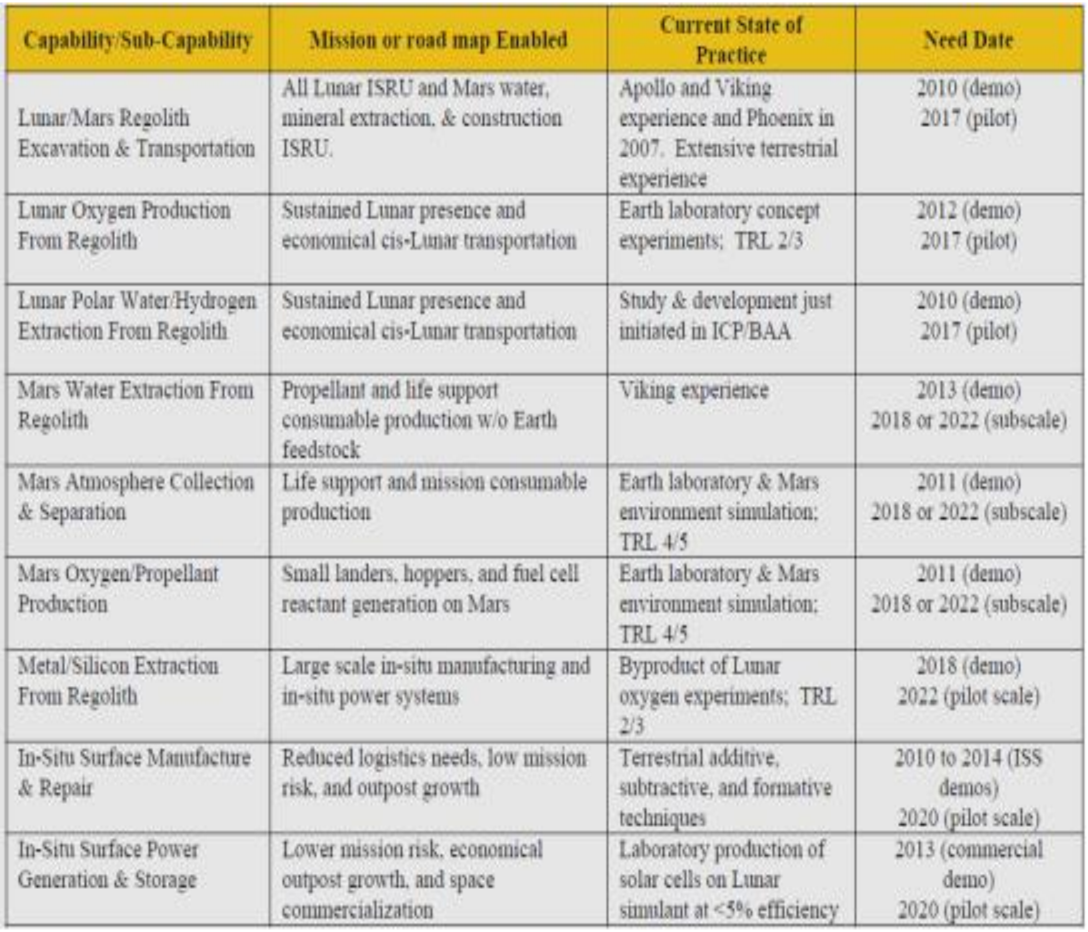
Image shows one unit doing final deposition; unseen are the other units creating lab-pure silicon, aluminum, dopants, etc., using multiple processes in ultra-clean conditions

Figure 2-19 Design for an Integrated Lunar Solar Cell Paving System [t-Space, 2005].

2.9 Assessment of Key SMR Processes

SMR technologies are currently immature and are critical to a whole new paradigm in space development costs. Advances in SMR systems readiness levels will significantly reduce risks for human space exploration and settlement. In general, technology development trades an R&D cost with more robust future systems performance. For example, the development of a lunar surface manufacturing or 3D metal printing capability could dramatically reduce the need for spare parts, increasing mission reliability and reducing long-term costs.

"The Key Capability table below for ISRU was compiled after a multi-step process. First past ISRU technology and mission studies and reports were examined to identify ISRU capabilities and quantify the benefits of these capabilities to extending or enabling individual missions and complete architectures. Then the identified capabilities were compared to each other to determine relative ranking. The capabilities/sub-capabilities listed in the table were those that were identified as supporting multiple ISRU capabilities (ex. Excavation and Surface Cryogenic Fluid Storage), that are applicable to both the Moon and Mars, or are critical for achieving significant mass, cost, and/or risk reduction benefits for individual missions or architectures as a whole. This list provides information on the missions enabled and the need date for this capability to be ready for incorporation into human missions" [Sanders, 2005]



Capability/Sub-Capability	Mission or road map Enabled	Current State of Practice	Need Date
Lunar/Mars Regolith Excavation & Transportation	All Lunar ISRU and Mars water, mineral extraction, & construction ISRU.	Apollo and Viking experience and Phoenix in 2007. Extensive terrestrial experience	2010 (demo) 2017 (pilot)
Lunar Oxygen Production From Regolith	Sustained Lunar presence and economical cis-Lunar transportation	Earth laboratory concept experiments; TRL 2/3	2012 (demo) 2017 (pilot)
Lunar Polar Water/Hydrogen Extraction From Regolith	Sustained Lunar presence and economical cis-Lunar transportation	Study & development just initiated in ICP/BAA	2010 (demo) 2017 (pilot)
Mars Water Extraction From Regolith	Propellant and life support consumable production w/o Earth feedstock	Viking experience	2013 (demo) 2018 or 2022 (subscale)
Mars Atmosphere Collection & Separation	Life support and mission consumable production	Earth laboratory & Mars environment simulation; TRL 4/5	2011 (demo) 2018 or 2022 (subscale)
Mars Oxygen/Propellant Production	Small landers, hoppers, and fuel cell reactant generation on Mars	Earth laboratory & Mars environment simulation; TRL 4/5	2011 (demo) 2018 or 2022 (subscale)
Metal/Silicon Extraction From Regolith	Large scale in-situ manufacturing and in-situ power systems	Byproduct of Lunar oxygen experiments; TRL 2/3	2018 (demo) 2022 (pilot scale)
In-Situ Surface Manufacture & Repair	Reduced logistics needs, low mission risk, and outpost growth	Terrestrial additive, subtractive, and formative techniques	2010 to 2014 (ISS demos) 2020 (pilot scale)
In-Situ Surface Power Generation & Storage	Lower mission risk, economical outpost growth, and space commercialization	Laboratory production of solar cells on Lunar simulant at <5% efficiency	2013 (commercial demo) 2020 (pilot scale)

Table 2-3, SMR Capability and Technology Needs [Sanders, 2005].

In addition, the list above reports TRL values for some SMR technology elements. Primary categories for SMR capabilities are derived from Sanders (2005). These include mineral extraction, transport, processing, manufacturing & construction, and volatile capture, refining & distribution.

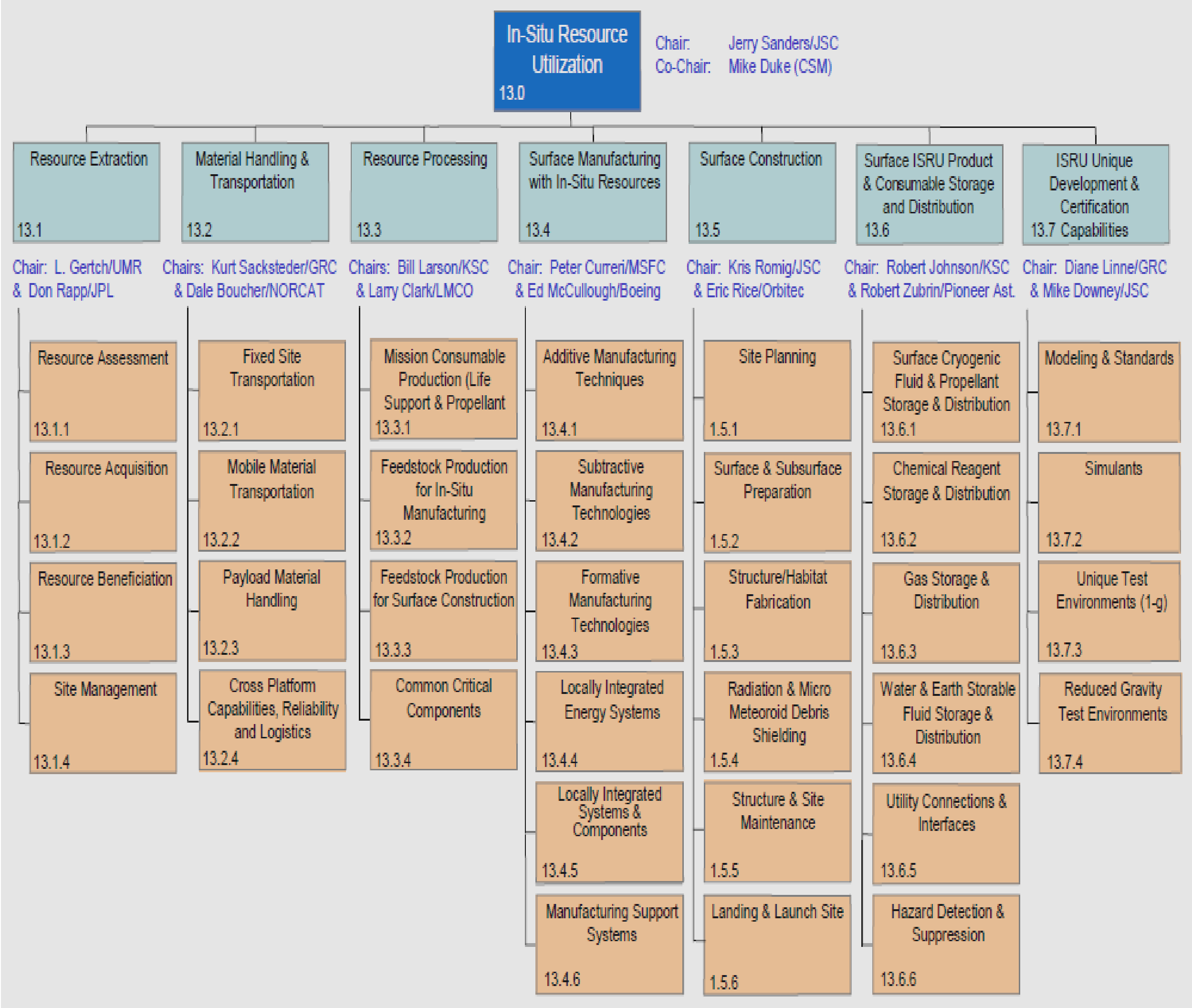


Figure 2-20, Primary SMR Categories for Capability and Technology Development [Sanders, 2005].

2.9.1 Resource Extraction

Extraction or severance of the SMR from its native environment is the first required step in a process that will result in a useful end product. Excavation is the most common method of extraction used on Earth today – a typical front-end loader is a good example. A special category called "mechanical excavation" is used by the mining and civil construction industry to describe systems that rip into harder or more consolidated rock. Due to the need to apply reactive forces during the excavation process (pushing a blade or scoop into the ground requires some kind of grip), anchoring systems for lunar and asteroid regolith should also be included in this category. For the Moon and Mars, excavation systems are straightforward due to the unconsolidated nature of much of the surficial material. For asteroids, basic variables for excavator design include resource type, spin rate, specific gravity, percent fragmentation and grain size distribution.

Planetary surface excavation capabilities have already been demonstrated on the Moon and Mars - specifically the scooping of regolith samples for transfer to a sample return canister (the Russian Luna 24 mission) or scientific instruments (the US Viking and Phoenix Mars missions). In addition, coring of lunar regolith samples was done during the Apollo missions, and grinding and analysis of rock samples have been done on a number of Moon and Mars missions. Preliminary work has been performed on acquiring and separating Oxygen from Mars atmospheric CO^2, as well as separation/filtration of dust during Mars atmospheric processing [Sanders, 2005].

2.9.2 Materials Handling & Transport

Materials transportation systems commonly used in mining include haul trucks, conveyors and rail cars. Handling equipment is typically related to the input and/or output sides of the above options. For example, a haul truck typically dumps its load into a crusher and the conveyor discharge ramp can be an excellent place for electrostatic or magnetic separation or size classification using a grizzly grid (an oversized sieve). Examples of specialized SMR materials handling systems include the possible use of magnetic raking for asteroid platinum group metals (PGMs), as well as hydro or air cyclones for separations in microgravity. Extraterrestrial experience in lunar materials handling and transporting includes the Apollo sample collection, raking and storage/containment devices. Mars samples have been robotically manipulated for limited analysis and disposal by the Viking, MER, Phoenix and MSL missions.

2.9.3 Resource Processing

A wide variety of mineral processing techniques are in use today providing feedstock to the global manufacturing infrastructure. Many of the chemical and physical separation and refining methods in use today on Earth will map directly to use in space – simplifying the need to find a feasible process. However, in the future the most efficient (optimal, which is better than feasible) means of SMR processing will likely take advantage of or leverage the unique environments found in space. Thus, creating a competitive advantage for the company or agency that discovers and patents it. An example of this is the use of the Mond or Carbonyl process for nickel and iron extraction and vapor deposition (a low temperature, microgravity-friendly process that utilizes carbon monoxide as its working fluid). The vast majority of near-Earth asteroids have abundant iron, nickel and carbon, making this an ideal candidate process for SMR application.

Lunar ISRU has a 30-year history of laboratory testing with little systems-level development. The successful production of Oxygen from returned Apollo lunar regolith samples has been demonstrated using the hydrogen reduction process. Several prototype systems for Mars atmospheric processing demonstrated Oxygen and Oxygen/methane production. Laboratory demonstrations were performed for more advanced Mars surface hydrocarbon fuel production including methanol, ethylene, benzene/toluene, and short-chain hydrocarbon mixtures. Materials processing demonstrations were done in microgravity in a number of Apollo, Skylab, and Spacelab experiments [Sanders, 2005].

Common industrial feed stocks can be found in asteroid, lunar and Martian regolith. The Moon is rich in metals (Fe, Ni, Al, Ti, Si - even Ca is an excellent conductor as long as it remains in vacuum) as well as glass that could be spun into fibers. Viking data shows the same metals may be available in the Martian regolith; thus, space metal production and refining technology could apply to the Moon, Mars and even asteroids. A number of lunar regolith oxygen production technologies that have been demonstrated at the laboratory scale leave behind pure metal in the spent regolith slag. This is due to reducing metal oxides (typically Iron) to liberate their oxygen for use in space transportation. However, to date no laboratory-scale experiment has actually separated pure metal from the remaining slag [Sanders, 2005].

Some biological processes could be valuable for SMR processing applications. Bioreactors for extraction of materials and synthesis of products are becoming commonplace on Earth; and, could be candidates for low power consumption SMR processes. NASA has even studied the use of synthetic biology to produce organisms that could process asteroid or planetary surface resources into useful products.

In space recycling of reagents will be likely for early SMR development due to the anticipated high cost of terrestrial resupply. The use of local materials for reagents (such as the use of hydrogen or carbon as a reducing agent) and catalysts will also be rewarded by reducing dependence on terrestrial resupply.

2.9.4 Space Manufacturing

Raw metals have little utility in space; yet, combined with modern manufacturing and 3D printing technology, could ignite a revolution in space capabilities. Paper studies suggest that 90% manufacturing closure could be obtained from the use of lunar materials, and nearly 100% from Mars materials [Sanders, 2005]. Asteroid materials hold similar promise. In-space fabrication and repair has been examined by NASA for its ability to reduce mission risk (particularly for human Mars exploration) and provide flexible repair options, reducing the need for redundancies and spares.

A long series of space manufacturing conferences were spawned and hosted by Princeton University professor Gerard O'Neil's Space Studies Institute. A rich history of space manufacturing systems design, costing and evaluation is recorded in their archives. The tendency to think big was much stronger in the post-Apollo era (the early 1970's) than it is today. Many ideas from that era should be re-evaluated from an economic and business perspective. Translating those concepts into the language of markets, costs, engineering feasibility and customer demand would enable access to the capital needed to build bold systems.

2.9.5 Space Construction

Space manufacturing is a necessary element of what could become an enabling emergent capability: The ability to construct habitats and industrial infrastructure in orbit and on planetary surfaces. This is key for the independence of future space settlement and industry; and, it holds the promise of expanding the sphere of human influence orders of magnitude beyond its current resource and spatial limits.

Lunar and Mars multispectral imagery and topographic data sets are steadily increasing in resolution, enabling preliminary site planning for important early settlement targets such as the highly illuminated lunar polar regions or "peaks of eternal light." Geophysical characterization (the key to stable foundations) is available at certain lunar and Martian sites as well as a growing list of asteroids. Most proposed space habitat construction methods have well-characterized terrestrial equivalents. Laboratory tests on lunar and Martian construction material fabrication includes sulfur and water-based concretes, glass fibers and rods, sintered bricks, and making more complex shapes using combustion synthesis [Sanders, 2005].

Early lunar and Martian construction efforts are likely to focus on landing site preparation and radiation protection. The Apollo landings unleashed a torrent of entrained particles that sandblasted everything in their path. The Surveyor 3 spacecraft was the only victim of this; and it provides an important data point for this phenomenon. Pavement or bricks, as well as flow channeling, will be required in order for multiple landings to be accomplished at the same site.

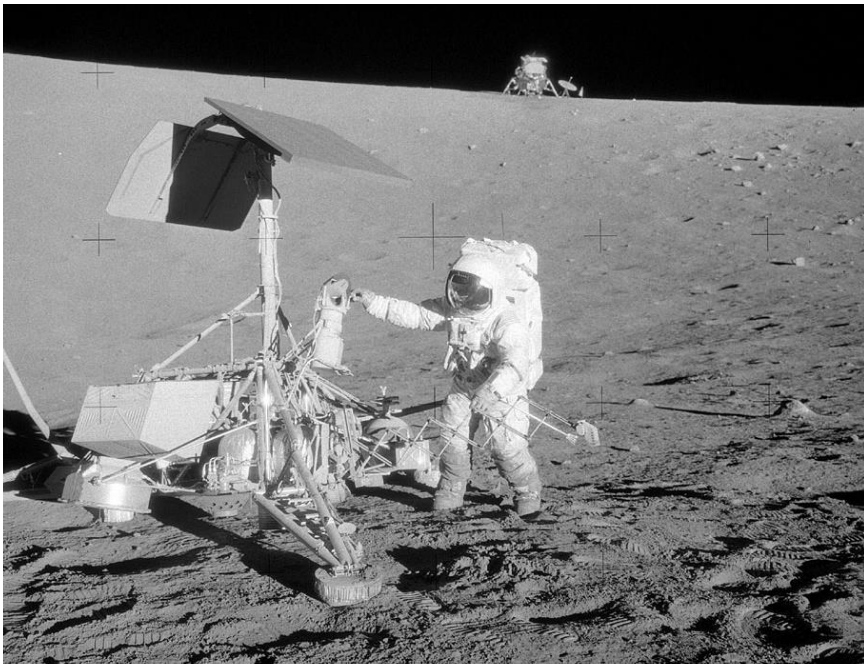


Figure 2-21, Apollo 12 crew at Surveyor 3 [image courtesy NASA].

Radiation protection will leverage SMR. A number of designs exist for burying early lunar habitats using raw or sandbagged regolith in order to protect crews from solar proton events.

2.9.6 Product Capture, Storage, Refining & Distribution

Capture of volatile gases is another important enabling SMR process technology. This could be done using adsorption by porous media, condensation on cold plate, or creating a pressure differential and using compression. Yet capture is far from sufficient. Mixed volatile separation will be needed (especially if lunar polar volatiles are mined as ices), requiring refining or distillation technology. After that, storage and distribution systems will be required, including fluid couplings for transfer of liquid or gaseous products to fuel cells or vehicles needing refueling. Fortunately, plenty of terrestrial cryogenic fluid management experience exists, including the potential for COTS solutions that could apply directly to space.

Waste heat dissipation is an important part of current spacecraft design, where thermal management issues can become complex due to sun angles and shadow. Indeed, radiator failures are a common problem in space. Thermal management issues limited the performance of at least one of the Apollo lunar rovers. Limited capacity cryocoolers have flown in space supporting science instruments including infrared cameras. Cryogenic fluid storage systems have flown in space for limited durations and (as of 2005) none had integrated liquefaction systems. Automatic and EVA fluid couplings have flown on ISS; and, a Helium II fluid coupling was built but not flown [Sanders, 2005].

2.9.7 Power Demands

One item that is very often overlooked is the tremendous need for energy during SMR operations. The level to just explore pushes the envelope in solar array power output while the demand for energy when humans are participating is huge. Most studies assume some type of physics power source that can provide constant power: day to day and in-space as well as on a planet. Small physics power plants are being developed around the world for small community utilization. These designs could be leveraged by both robotic and/or human SMR ventures. An additional choice would be to use the volatiles that are being mined as sources of power. NASA has studied planetary power sources extensively. The concept is basic: mining and processing SMRs will use massive energy. The beauty of the situation is that once the SMR teams [robotic and/or human] are in place with sufficient power sources, energy becomes an SMR and can be sold.

2.9.8 Status of SMR Technology Development Programs[3]

The cancellation of the Constellation program, which was developing capabilities for human lunar and Mars exploration, also reduced NASA's investment in SMR technology maturation. The heritage argument (if a space system has not been flown in the past, it does not belong in today's mission planning because it would introduce too much risk) has been used all too often to suppress the incorporation of SMR into NASA's mission and architecture planning. The Constellation program marked the beginning of a reversal in this philosophy.

SMR technology development is being undertaken by public and private agents in the US, Canada and Europe, with a growing base of support. The potential for commercial applications and future profits adds incentive for private investment into technology maturation. Interest in lunar and asteroid resources is being publically announced by a growing number of private entities including Shackleton Energy Company, Planetary Resources, Deep Space Industries, Golden Spike and Moon Express. This clearly implies commercial interest in maturing SMR technology. Given the preponderance of half-mature technologies at NASA, CSA and ESA (with many TRLs in the 3-5 range), this would create an incentive for partnerships or spin-out opportunities. The appearance of private agents could also introduce an element of secrecy or stealth regarding true TRL levels.

2.10 Research and Development Concepts

The development of mining techniques for the environment of an asteroid, on the surface of the Moon, or Mars will be unique and

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[3] Note: Two further technologies need to be developed rapidly; however, they are not discussed at length in this study as they are supportive technologies. The first is movement of mass in space with higher ISP devices such as VASIMR and ion engines. The second is power at the necessary locations – solar is a weak sources and especially worrisome when going beyond the Earth's distance from the Sun.

surprising. A straightforward game plan for research and development of mining technologies is shown in the next few paragraphs. The steps are shown in a list below with more detail expanded within four key risk reduction activities;

- Space Demonstrations
    - Bag and Capture
    - Asteroid Nickel Recovery
    - Fluid Physics
    - Chemical Reactions
    - Physical Processes
    - Heating Methods
    - Forms and Substrates
    - Microgravity Digestion
    - Microgravity Deposition
    - Integrated Mining and Manufacturing
- Laboratory/Ground Demonstrations
    - Asteroid Nickel Recovery
    - Meteorite Chemistry
    - Meteorite Digestion
    - Fragmentation
    - Sensing and Control
    - Nickel Deposition
    - Forms and Substrates

The following are expansions of the above showing some components of an R&D Plan:

1) Space Demonstrations – Bag and Capture

Approach: Demonstrate the deployment and sealing of an inflatable membrane around a piece of satellite debris, then inflate system to test actual vs. designed leakage rates.

Research Highlights: Develop methods of capturing a small space object using a bag. Demonstrate bag deployment and sealing in earth orbit. Inflate bag to test leak rate. Dual use for asteroids and debris

Benefits and Results: Creates dual use technology for satellite or debris recovery and asteroid resource processing. Creates independent economic return opportunity, reducing business risk.

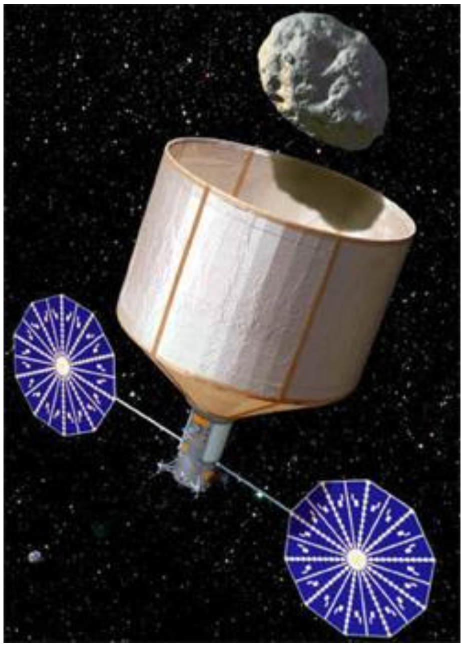


Figure 2-22 Bag and Capture [Keck]

2) Space Demonstrations – Microgravity Digestion

Approach: An integrated microgravity digestion test will form a critical milestone in process validation, particularly if meteoritic source material is used in an on-orbit demo.

Research Highlights: Demonstrate integrated subsystem for nickel deposition in microgravity conditions. Return of metallurgical samples and depleted source materials will yield important scientific data.

Benefits and Results: Provides a venue to work out the bugs for an integrated Ni deposition systems technology. Reduces technical risk Generates promotional milestone. TRL9 certified deposition system.

3) Laboratory/Ground Demonstrations – Meteorite Chemistry

Approach: Carbon monoxide could be used to dissolve nickel, iron and cobalt from a wide variety of meteorites to discern process dynamics; but, this needs to be verified in the lab.

Figure 2-23, Microgravity Digestion [Artwork, Nat White]

<u>Research Highlights:</u> Digestion of asteroid nickel can be demonstrated on the ground using existing meteorite samples. Carbonyl process efficiency and reaction kinetics can be directly measured to show process robustness and generality
<u>Benefits and Results:</u> Develops a heuristic for process applicability vs. asteroid class. Demonstrates how generalized the carbonyl process can be. Could prove that the process will work for any class of asteroid.

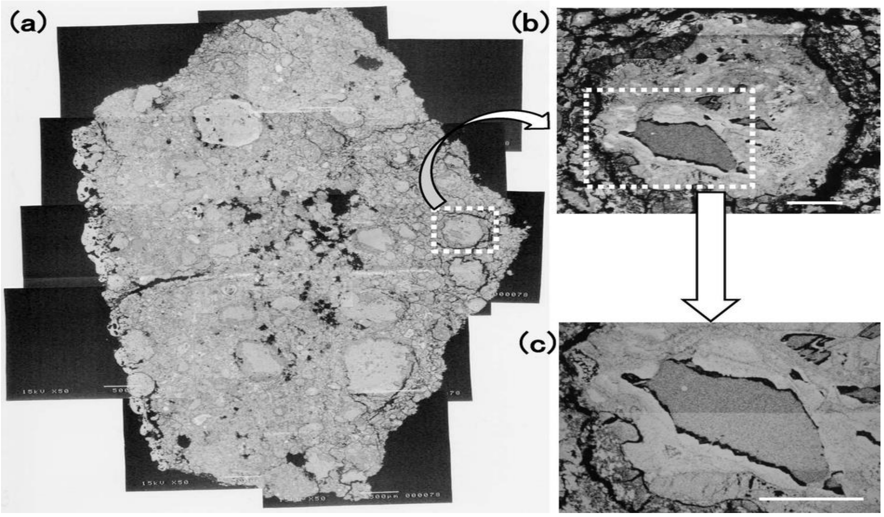


Figure 2-24, Meteorite Chemistry [Hidaka 2012]

4) Laboratory/Ground Demonstrations – Nickel Deposition
<u>Approach:</u> Solid materials (particles, thin films, shells or wires) can be deposited on a substrate by a gas phase reactive species – this is a process known as chemical vapor deposition.

<u>Research Highlights:</u> Demonstrate nickel metal deposition as precursor gases travel over a heated substrate. Key process variables: temperature, partial pressure of precursor and byproduct gases.
<u>Benefits and Results:</u> Demonstration of the Mond process for nickel deposition. It would raise the TRL of candidate asteroid processing technology. This demo would be particularly useful if the precursor gases were derived from meteorite samples

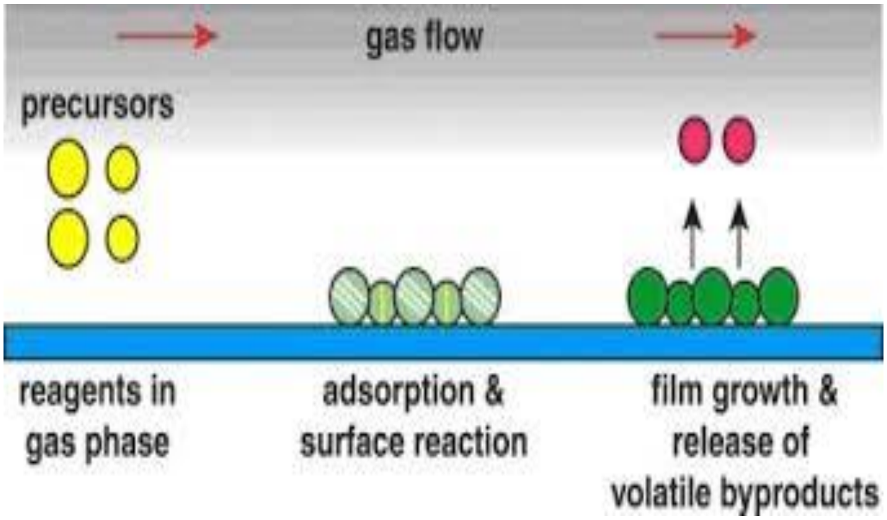


Figure 2-25, Nickel Deposition [AZoNano]

2.11 Summary of SMR Systems

The summary of this chapter dealing with concepts to mine minerals in space can best be illustrated by showing an example where SMR capability will enable a tremendous capability:

Enabling Human Expansion:

A vision which opens up the solar system to human development must be powered by commercial entrepreneurs. Recently, two teams have announced they are going to Mars:

- Bas Landorp has a program, Mars One, where a colony will be developed on the surface of Mars within the next 15 years. He has 20,000 people signed up for the one-way exploration and development of Mars into a productive colony.

- Elon Musk has stated that he will have his company, SpaceX, develop and exploit the reusability of inexpensive launch capabilities, leading to a colony of 10,000 people on Mars "within his lifetime."

One key factor that governments are overlooking today is that leaders of start-up commercial companies are enormously rich and have taken on a "mission" to expand into space with revolutionary approaches. These two different dreams in going to Mars have become executable programs for teams of people working for companies with vision and resources. However, to enable this type of human expansion into the solar system, space mineral resources must be developed and executed prior to the previously mentioned ventures. This recognition of a "truth" will surface within the next few years as the difficulty of providing resources from the surface of the Earth becomes extraordinarily intimidating. The solution, of a problem not articulated up to now - commercial exploitation of space mineral resources - must be established as a service to these and other ventures of human expansion. Major functions must be conceptualized, developed, funded and placed in the proper environment to enable a robust road to future Mars human expansion. Two of these are:

1) In-situ resource processes – proven, and available to the Human Colonies of the Moon and Mars.
2) Fuel Depots located at diverse locations such as Earth-Moon L-1 or surface depots on the Moon or Mars. Fuel Depots would provide large quantities of rocket fuel, oxygen, hydrogen, water and air at commercial prices.

The ability to rely on commercial processes to provide these products during trips to Mars and the Moon will enable commercial human expansion. Investments into space mineral resource development will enable far more expansion projects than are envisioned today and will enable both Elon Musk's and Bas Landsdorp's projects. Dreams, even ones articulated by visionaries with resources, must be enabled by practical logistics projects that produce new commercial ventures. The development of fueling stations in deep space will allow effective human transportation around the solar system. Commercial SMR ventures will enable human spaceflight to the Moon and Mars; and, they will make a profit along the way.

Chapter Three, Market Approach

3.0 SMR SYSTEMS CONCEPTS

A wide array of mining and mineral extraction technologies exist today. Because of the similarity between space and terrestrial resources, much of this technology should readily adapt to the unique environmental physics of the Moon, Mars and asteroids. As such, long-term customers for SMR could include users on Earth as well as in space. It is the purpose of this section to develop and demonstrate economic methods in order to estimate the market value of SMR commodities in both situations. Chapter Six will go into depth on analyses of the approaches by using economic models. While a thorough economic analysis is impossible without more information, there is sufficient current data available to constrain or bound feasible solutions, yielding critical insights into likely future investment behavior. This approach can also help identify weak assumptions (ones that need more investigation) as well as enabling technologies (opportunities for private or government investment). By definition, emerging market opportunities never have full information; therefore, they remain in the category of high risk investments. Recently this lack of information for future space ventures was discussed in the British Interplanetary magazine, Spaceflight. It begins:

> "In the rough and tumble world of commercial marketing it is an axiom that belief in a projected profit precedes investment; nobody can prove a positive by eliminating a negative. So it is impossible to know for sure if the profit is real until the investment provides the funds to complete development. In the world of satellite launchers that means a lot of faith is needed in the corporate framework of the new developer and, by definition, "new" means "no precedent." That in turn means "no parallel" against which to judge success or failure." (The British Interplanetary Society, 2012).

To expand on this concept, SMR marketing should incorporate the following concepts in their sales program.

- Dream Big,
- Sell Aggressively,
- Design to the future Market, and
- Convince investors that there are big profits for those who take early risks.

3.1 SMR Product Value – An Example

The value of SMR is a projection of many factors, to include price of launch, mass to orbit, percentage of the mass to orbit that can be sold, and location of sale. To put this into perspective, one example will be used. The product to be sold will be water [can be leveraged into drinking water, hydrogen, oxygen, air, power, and fuel]. The presentation below will illustrate the price for sale at the location of choice. If one were to deliver water from the Earth's surface, what would it cost? This calculation is an estimation of location value of water, based on many assumptions and educated projections. The locations being compared are LEO, GEO, EML-1, and Asteroid-Lunar-Mars Surfaces. The basic assumptions are derived from the web page of the Falcon Heavy vehicle [projecting best prices and capabilities, yet to be proven]. The assumptions are:

-Price:	$77-135 Million [choose $100 Million as standard]
-Mass at Pad:	1,462,836 kg
-Water % Mass at Location:	25% of payload reaching LEO, GEO, Asteroid, EML-1
-Water % Mass at Location:	10% of payload reaching Mars [25% to transfer orbit, 40% to move to surface]
-Moon Surface	used Apollo numbers [Lunar Lander on surface vs Saturn V Mass]

	Mass kg	Payload [water] Mass kg	Price per kg	Price per metric ton
On–Pad	1,462,836			
In LEO	53,000	13,250	$7,547	$ 7.5 million
At GEO	21,000	5,300	$ 18,868	$ 18.9 million
At Earth-Moon EML-1	20,000	5,000	$ 20,000	$ 20.0 million
On Asteroid surface*	14,000	3,500	$ 28,571	$ 28.6 million
On Lunar Surface**	7,314	1,828	$ 54,705	$ 54.7 million
On Mars Surface***	13,200 (Insertion)	1,320 [surface]	$ 75,757	$ 75.8 million

*L-1 and Asteroid estimates based upon delta V comparisons

**used Apollo ratio of mass of Lunar Lander to Mass of Saturn V

***from Mars insertion mass to surface required reduction to 10%

Table 3-1, Value of Water

The above analysis shows that the market value of water delivered to a location in our solar system can be priced. If you can produce and deliver this SMR product [water] for less than the Earth based price, profits can flow. Mining large quantities of water on an asteroid (or Lunar surface) and bringing it to EML-1, as an example, would accomplish two significant goals: (1) enable more mission related mass to be launched from Earth, and 2) open up an SMR marketplace at the Earth-Moon EML-1 space depot.

During a recent discussion with a true rocket scientist, [Cook, 2014] two concepts emerged that have significant bearing on the SMR approach.

(1) The discovery and processing of water on the Moon, Mars or an asteroid will enable a variety of resources that are essential to exploration beyond LEO:

- Fuel: oxygen hydrogen and peroxide
- Air: oxygen combined with residual nitrogen
- Water: drinking water will be required, while washing and

cooking will be desired.
- Radiation protection: layers of water are an excellent absorber of radiation.

(2) A realization that:

<u>“Water will be the Currency of Space!”</u>

3.2 Primary Market Descriptions

At each near-Earth destination, the demand for commodities and finished products will vary with current and expected activities appropriate to that location. As defined in chapter one, the three approaches for SMR are:

- <u>SMR Approach 1 – Localized Utilization:</u> This will be the initial approach, as it is the simplest, and can leverage early exploration and movement beyond LEO. By gathering and using local resources, missions can be extended.
- <u>SMR Approach 2 – Transport Materials to Processing Nodes:</u> This concept expands humanity's reach beyond LEO by offering power generation, storage facilities, additive manufacturing, and other capabilities/equipment at appropriate locations. The first activity would likely be energy generation and storage of oxygen, hydrogen, nitrogen [potentially] and carbonaceous materials for water, fuel, propellant, and for plant growth at a “space depot.” Furthermore, there are some resources that are required for processing of asteroidal SMR, carbon monoxide, for example. The Mars atmosphere has a substantial fraction of CO, this may well be less expensive to purchase and transport from the surface of Mars to the asteroid belt than transporting all the way from Earth, requires considerably less time, too. The objective is to identify resources which may be of indirect value in addition to those of direct value, particularly to other space-based ventures.
- <u>SMR Approach 3 – Deliver SMRs to Earth’s Surface:</u> The return of goods and services, as well as resources, has been down-played over the years. However, the value of bringing resources back to Earth greatly enhances the reasons to invest in SMR missions.

Remember that SMR will be a part of the overall development of the space economy. This includes space manufacturing, extraction of fuels other than those shipped from Earth to supplement existing and future infrastructure and other space activities. They will, in turn, determine the expected demand for the products of space mining. Moreover, in the case of valuable minerals, such as platinum group metals (PGM), there exists a potential demand on Earth. The SMRs provided to the following markets will come from asteroid or lunar surface mining. Each have significant advantages or disadvantages to be compared as commercial mining ventures are established. Potential markets for SMR in each of these destinations will be elaborated upon below.

SMR Approach 3: Return to Earth – The return and sale of asteroid materials into terrestrial markets has been underway for many years because asteroids are the only SMR with its own sample return program. This "rain of fire and ice" is responsible for many ore bodies in commercial production, including the nickel mines of Sudbury, Canada. About 100 metric tons of meteor samples rain down upon the Earth each day [nasa.gov]. Robust trade and sale of meteorite samples is a daily occurrence. As costs for space infrastructure drop, the number of asteroid-derived products sold on Earth will naturally increase. Short-term terrestrial markets for samples deliberately collected and returned could include samples for both science and collectors. This includes PGMs, rare Earth elements (REEs), nickel & industrial metals, microgravity-processed materials (e.g., protein crystals), other biological research, and so on. Longer term markets could include lower value materials. Long-term terrestrial markets could include industrial products and specialty manufactured goods. The NASA NIAC Robotic Asteroid Prospector project [Cohen, 2013] recommended a process for evaluation of these elements, analyzing the value of PGMs and REEs returned to Earth from a near-term mission.

> *"The likelihood of orbital manufacturing facilities in the 20-year time frame is high, and is strongly linked with the growth required to enable asteroid mining endeavors. Specialized niche-market products that could benefit from orbital manufacturing include exotic alloys, metallic-foam based catalysts or high-purity electronic components"* [Blair, 2000]

> Note that the NASA microgravity research program (1998-2004), ISS Program Office, and Space Partnerships Program have conducted significant prior research for potential products made in space and returned to Earth. Some of this work continues today with the startup company NanoRacks. Many of these could be reevaluated for SMR contribution.
>
> Rationale for long-term use of space resources on Earth include Hubbart's peak, where finite or non-renewable mineral resources are theorized to have a peak in productivity, followed by a gradual decline as the resource is used up.
>
> *"Sustainable development is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987, p. 8). This has become the most accepted definition internationally. … One can ask whether we can maintain this level of consumption and still fulfill the requirements of sustainable development, particularly in view of the fact that we have consumed more resources since World War II than during the whole of our long history before that."* [Wellmer, 2007]

Of course, the return of SMRs to the surface will require some technological advances because of the phenomenal gravitational pull as they approach. The traditional manner is to use ablative shields and guide them into a predetermined “safe” landing zone. Another approach could be available in the future with a space elevator. The Apex Anchor provides a stable location at 100,000 km altitude. It is a pathway to anywhere in the solar system with its inherent potential energy and horizontal velocity from the rotation of the Earth. The location has a natural 20 % gravity acceleration away from the Earth. As a result of easy access from/to the Earth, the Apex Anchor spaceport is a premier location for moving space mineral resources as well as being a principle location for manufacturing and assembly of space systems. Returning product from commercial space ventures could be a major user of a space elevator infrastructure.

The fact is that Earth is a finite system with limited resources. For mankind to continue to live an affluent lifestyle on the surface of Earth, it may become necessary to import raw materials.

SMR Approach 2: Deliver Product to LEO – The existing market is the International Space Station (ISS) and remote-sensing spacecraft in equatorial and polar orbits. Both ISS and remote-sensing spacecraft gradually lose altitude due to atmospheric drag. The ISS, which loses an average of 135 meters in altitude per day, is periodically reboosted by Progress resupply ships, consuming about 7 tonnes of propellant per year. Remote-sensing spacecraft eventually go out of service when their orbits dip too low. Both would be customers for cost-effective reboost services using asteroid-derived propellant. The ISS also consumes water that could be supplied from asteroid sources.

Future LEO markets likely will feature additional space stations operated by national governments or industry, many with specialized uses compared to the all-in-one approach of the ISS. In order to achieve better microgravity conditions, for example, some stations will operate robotically and be only periodically visited by crews to restock inputs and harvest outputs. Others may be rotating structures to provide full or partial gravity for uses where gravity is advantageous. For all these types of stations, asteroid resources can be used to build pressure vessels, solar arrays, and structures such as the trusses launched to the ISS to position and hold solar arrays and radiators. Solar arrays launched from Earth may have their output boosted by adding mirrors fabricated from asteroid metals. Crewed space stations will need replenishment fuel, gasses and water. All stations will need their orbits raised to counter atmospheric drag. Some stations may deliberately fly much lower than the ISS to make reaching them less costly for vehicles rising from Earth, and burn asteroid volatiles in substantial quantities to counter the drag.

SMR Approach 2: Deliver Product to GEO – The existing market centers on communications satellites, which consume propellant in order to maintain their assigned position in the geosynchronous ring and to prevent drifting north-south so far that fixed Earth dishes lose contact with them. Once their fuel is exhausted, communications satellites no longer can maintain their required fixed positions. Several companies now offer "life extension" services that depend upon fresh propellant launched from Earth; asteroid-derived propellant can be a lower-cost source for this task. While virtually all communications satellites use a variation on hydrazine as their station-keeping propellant, several of the terrestrially-based life extension services don't seek to actually refill the propellant tanks of comsats; but, instead, they clamp on a shepherding vehicle using its own tanks and motors. Shepherding spacecraft can be designed to use whatever asteroid-derived fuels are the most cost effective to extract from the volatiles found on NEAs.

Over time, communications satellites may be replaced by permanent communications platforms designed to be refueled and enhanced with add-on solar arrays and spot beam antennas as their service regions evolve. Communications platforms will solve the mass and fairing-size limits of existing launch systems by adding mass and structure after launch. Violent vibration during launch also tends to limit antenna design and size. NEAs rich in metals and silicates can supply the materials needed to fabricate truss structures, solar cells and antennas for expansive communications platforms with the power and giant antenna size required to deliver very high bandwidth communications to any spot on the globe, no matter how remote they are from the established communications grid.

SMR Approach 2: Deliver Product to Earth-Moon Lagrangian Points – These are destinations with far less current activity, but with huge potential for growth, especially the Lagrangian points (EML-1 & EML-2) in the Earth-Moon system. These are balance points where spacecraft can maintain position with minimal expenditures of station-keeping propellant. The balance points EML-1 and EML-2 in the Earth-Moon system, for example, are located on a line extending out from the Earth. EML-1 is about 84% of the distance to the Moon, located about 58,200 km above the near side, and EML-2 lies beyond the Moon's far side by the similar distance, 64,700 km. As the Moon revolves around Earth, spacecraft in EML-1 and EML-2 can maintain their relative positions to the Earth and Moon with minimal energy expenditure. Both have been considered useful staging locations for crewed expeditions to the Moon and Mars. Earth-Moon EML-1 offers an attractive place to store and process arriving asteroid material, as well as to stage propellant depot operations for lunar-derived fuels. Some output will serve local needs (to outfit missions to the Moon and Mars) and other products will be shipped to GEO and LEO. In general, the higher an object is in Earth's gravity well, the less energy is required to reach that location from the orbit of a NEA; this favors EML-1 as the point of initial processing. However, the “best” trajectories to reach each potential receiving location, starting from a multiplicity of potential NEA orbits, are yet to be fully calculated. Due to low outbound energy requirements, EML-1 offers a unique opportunity to service many inclinations in Earth orbit without the usual plane change penalty. This makes it an extremely valuable and unique location for inbound as well as outbound orbital transfer. Indeed, an EML-1 traffic control authority will be an early policy requirement to minimize scheduling and operational conflicts.

If this Lagrangian point becomes a transit location for crewed expeditions to the Moon and Mars, propellant will be a major commodity. If launched directly from Earth, some 90% of the mass of a crewed Mars expedition would be propellant. By pausing at Earth-Moon EML-1 to refuel, much more of the expeditions’ mass can be useful equipment and supplies to reduce risk and expand capabilities. Alternatively, the total mass launched from Earth can be reduced to make the missions more affordable.

A major challenge to Mars expeditions is the radiation that would be sustained by the crews over each six to nine month leg of the trip. (ISS crew members do not experience high radiation dosing due to protection from the Earth’ magnetic field.) Radiation shielding made from asteroid materials can be added to expedition vehicles at EML-1 at far lower cost than launching this bulk material from Earth. For radiation shielding, raw rock will suffice, although water extracted from asteroids would be more effective per pound. Heat shields to protect vehicles during Mars atmospheric entry also can be added at EML-1, at similar savings compared to launching them from Earth.

SMR Approach 2: Deliver Product to Lunar orbit – Low Lunar orbit [LLO] is a destination that could serve future crewed and robotic activities on the lunar surface. Spacecraft taking off from the Moon might be fueled with propellant extracted from cold traps at the lunar poles. Spacecraft descending to the Moon might use fuel produced from NEAs processed in lunar orbit. Other scenarios would have both Earth-Moon and Earth-Mars traffic routed via the Earth-Moon EML-1 point where NEA processing would deliver propellant useful on both routes; however, LLO is the least likely location to process asteroid material.

First, it places processed asteroid materials in the Moon's gravity well restricting its mobility. In addition, the construction of large-scale industrial, observation or communication platforms in Lunar Orbit has limited commercial use; and, Mars expeditions would not detour down into the lunar gravity well to get supplies. Even Moon expeditions would have more flexibility in reaching diverse lunar surface destinations leaving from EML-1 than from a fixed lunar orbit. In addition, the instability of Lunar Orbits due to gravitational anomalies on the lunar surface makes its long-term use hazardous.

An orbit around the Moon was suggested in the Keck Institute study of asteroid retrieval primarily because any asteroid that drifted out of control would eventually impact on the lunar surface. This safety feature comes into play only after an object is delivered; however, during transit, the risk from that object remains. Therefore, safety should be achieved by never transporting an object large enough to survive Earth entry, regardless of the in-space location chosen for processing.

Another issue with lunar orbit is that it is not near any current or near term market. At some point in the next several decades, spacecraft heading to the lunar surface might pause in lunar orbit to take on propellant supplied by asteroids. On the other hand, Earth-Moon EML-1 may be the preferred location to tank up on the way to the Moon because any longitude and latitude on the Moon can be reached equally easily from EML-1. By contrast, a processing station in lunar orbit is confined to a specific inclination and period. Only a subset of lunar surface locations can be easily and quickly reached from a lunar orbiting fuel station locked into a specific orbit.

SMR Approach 1: Process on Lunar Surface – In addition to planned government missions, commercial tourism and settlements on the Moon have been discussed for a number of years. The Google Lunar X-Prize (GLXP) is offering $30M to a private company that puts a rover on Earth's nearest neighbor. The recent announcement by Golden Spike offering tourist missions to the lunar surface as well as Bigelow Aerospace's planned surface habitats and Excalibur Almaz Limited's circumlunar tourism flights demonstrate that the Moon may be closer to private development than previously believed. Therefore, the lunar surface could be considered a “near-term” market. Processing of ice into air, water and heating fuel would probably be the initial commercial products.

SMR Approach 1: Process on Phobos / Deimos – An island of resources in Mars orbit, Phobos and Deimos are thought to be captured carbonaceous asteroids with reasonable potential for hydrated salts (a source of easily-extractable water). If this proves true, they both could become way-stations for inbound and outbound Mars settlement missions; and, either would make a natural target for commercial development due to proximity to market as well as favorable composition. In addition, due to their low gravity, they would be space station-like docking targets and natural places to place propellant refueling depots. A growing industrial support staff as well as settlers would form an important market for goods and services.

SMR Approach 1: Process on Mars Surface – Recent private interest in the settlement of Mars includes the Mars-One concept of Bas Lansdorp and Elon Musk’s vision of an 10,000 person strong colony within his lifetime. The attention of high net-worth individuals is propelling Mars into the commercial mainstream. When fully developed, it represents a set of interconnected future markets spanning from Low-Earth orbit all the way to the surface of the red planet. Mapping the timing, characteristics and likelihood of Mars-bound human market segments will inform business opportunities for the next century, as well as new fortunes and empires. This concept of 10,000 Mars inhabitants by 2070 forms the baseline for the economic modeling and analyses chapter.

3.3 SMR MARKET ASSESSMENT AND ECONOMICS

The challenge of translating the budding potential of space mineral resources (SMR) into solid economic reality will become a vast human enterprise as it unfolds. It will consume generations’ worth of capital input as well as creative thought; and, it will depend upon the hard labor of man and machine to make it real. The output of this effort could become a functional network of space infrastructure capable of sustaining and expanding human life into places never imagined in previous centuries, a network that also provides direct benefits to its home world. Sober-minded economic analyses are required in order to cast SMR into a proper framework and to create a valid context for understanding whether there is an actual basis for present and/or future value of SMR to both public and private stakeholders. In order to gain the approval of real-world decision makers in government and commercial realms, this translation of intangible to real assets must be rooted in solid business reality. This reality is the bread and butter of modern business and management schools, whose tools will be needed in order to evaluate SMR in a relevant and realistic context. Market uncertainties and technical risks dominate estimates of the present value of asteroid resources, underscoring the fact that risk capital will be needed (and is showing up) to prime the pump. The risk-adjusted cost-of-capital rate for discounting future value estimates must account for this fact and must be high enough to properly evaluate SMR investment opportunities on a level playing field with terrestrial alternatives. By casting market, technical and legal risks into economic terms, a quantitative framework can emerge in order to measure the value of the various investments needed for SMR maturity. A summary of the upper limit for sale prices for one ton of material [water] is shown in the next chart. These numbers are open estimates, but reflect the magnitude of the estimated cost to lift the material from the Earth's surface, and as such are the criteria for target upper limit of sale price, (although they use a very aggressive uplift model based on a reusable Falcon 9 Heavy).

Upper Limit Sale Price of One Metric Ton of Water [or minerals]

In US$ million	LEO	GEO	EML-1	Lunar Orbit	Lunar Surface	Mars Orbit	Mars Surface
One Ton of Water	$ 7.5	$ 18.9	$ 20.0	$ 28.1	$ 54.7	$ 65.0	$ 75.8

3.3.1 Prior SMR Market and Economic Studies

This section will delve into a bit of the history of SMR economic analysis. The concept of economic sustainability for space development and settlement is not new. It is a recurring theme for a simple reason: Closing the cost loop by making a frontier pay for itself is the very definition of sustainable behavior. This, of course, depends upon full-cost accounting and the absence of externalities.

3.3.1.1 Economic History of the Space Frontier

In 1962, the first privately financed space launch put the Telstar research satellite into orbit. Sponsored by AT&T, Bell Telephone Laboratories, NASA, GPO of the United Kingdom and National PTT of France, the successful transmission of a television signal, via satellite, over the Atlantic Ocean brought Earth orbit into mankind's economic sphere. Between 1964 and 1974, five communications satellites would be launched into geosynchronous orbit (GEO), extending the global economy further into space. From these humble beginnings to today, nearly 1,900 communications satellites have been launched – more than half of them for civilian commercial use. Today's economic activity in Earth orbit has expanded into several types of commercial satellite and space-based services providing remote sensing, weather, navigation and even privately-funded microgravity research to a growing number of users. Much has been written on the business of space business, including a growing number of trade journals and magazines. Today's global communication satellite industry alone generates over $200Billion (US) in annual revenues.

"When a new frontier is opened, the new territory always looks vast, empty, hostile, and unrewarding. It is always dangerous to go there, and almost impossible to live there in loneliness and peril. The technological capacities of the time are always taxed to the utmost in dealing with the new environment. The explorations require huge investments of both public and private funds, and the returns are always hazardous at first. A few enterprises succeed fabulously, but many fail through inadequate planning or bad timing. The organization, capital, and equipment required for the first exploratory efforts are so large that people tend at first to think only in terms of governmental and military action; and only later do they conceive the new territory as simply an extension of their present territory and their present economy." [Cordiner, 1961]

Due to advancing technology, and newly available risk capital from Silicon Valley billionaires, a new frontier is opening up for human settlement. This frontier will depend upon SMR as the most fundamental enabling and constraining factor. Humans have always ventured forth to new places provided there are resources available to sustain life and create new wealth. Commercial technologies under development that facilitate SMR include inflatable habitats (Bigelow Aerospace), private space capsules (SpaceX), lifting bodies with thermal protection (Sierra Nevada Corp), as well as reusable rockets (SpaceX) and upper stages (Xcor). Some of the venture capital that is behind the commercial development of these systems will no doubt do very well. Technology will be covered in more detail in a different chapter.

3.3.1.2 Historical SMR Economic Analysis

Critical analyses of space resource business cases have been underway for some time. Early anticipated use of lunar SMR would produce rocket propellant for government and private users. A refueling station at an early lunar outpost could dramatically reduce the mass of a steady-state lunar transportation system by eliminating the heavy expendable first stage of a two-stage lander. Enabled by the physics of aerobraking, lunar propellant supply could even extend its reach past lunar orbit toward low-Earth orbit. This is because access to LEO from the surface of the Moon requires roughly 5% of the energy of launch from Earth's surface, providing nearly 20:1 energy leverage for lunar products. Detailed economic analysis of a lunar ice mining architecture identified feasibility criteria for cost and market size that would attract private investment [Blair, 2002]. This study will be covered in more detail in a later chapter. Current expendable upper stage vehicle technology can and is being progressively modified for re-use [Kutter, 2007], making this type of commercial system a real possibility. Surface mobility benefits for refuelable rovers could be equally significant. A source of fuel cell reactants on the lunar surface could enable energy-intensive applications such as mining, construction or robust and power-rich human exploration operations using a closed-cabin rover [Baiden, 2009].

Space or lunar solar power systems could someday satisfy growing energy demands of the home planet. Orbiting solar energy collectors would beam power using microwaves or light, putting commercial power directly into Earth's energy grid [Criswell, 2003]. This ambitious vision would represent the largest engineering project in space history (as shown in the Figures below), drawing upon SMR as an industrial materials feedstock [Bock, 1979]. A similar process could build commercial or residential real estate in Earth orbit. Detailed analyses of system fabrication and deployment costs vs. high-value terrestrial power customers are underway [Mankins, 2012]. A number of technical breakthroughs may enable near-term space solar power. In-space customers for space solar power might become a near-term premium-value market segment for these systems.

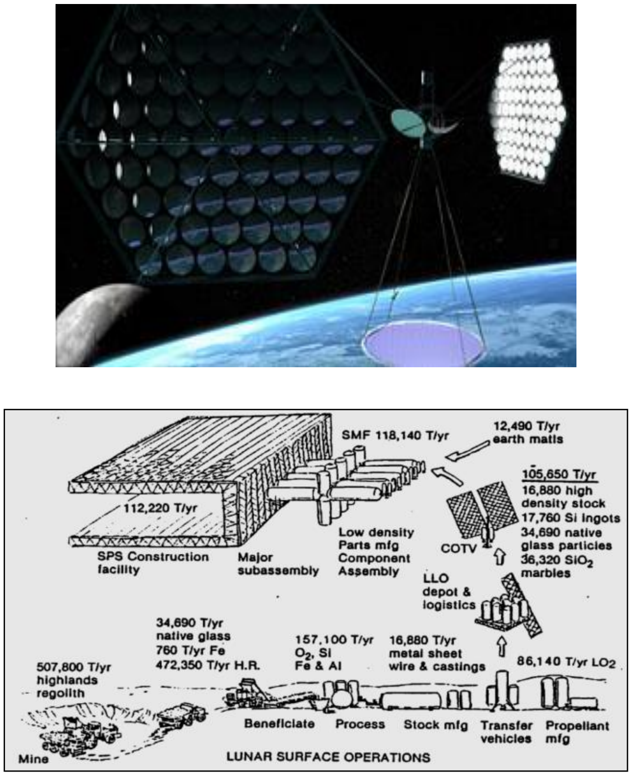


Figure 3-1, Concept of Orbiting Space Solar Power (Courtesy Mafic Studios); + materials flow to orbiting Solar Power Satellite [Bock, 1979].

Asteroids have recently gained the attention of the press, and for good reason. They offer a diverse set of resources that are ideal for supporting human life and industrial expansion. These resources include raw (not oxidized) metals, hydrocarbons (for plastics), volatiles (which can be used for propellant and life support) as well as silicates (which can be used to manufacture glass and ceramics). In addition, a few of them contain concentrations of precious metals of higher grade than today's best mines. This is due to the so-called "iron catastrophe" that drove heavy metals to Earth's core early in its molten history.

Many of the heavy metals on Earth's surface were put there by later asteroid bombardment.

"Recent discoveries of near-Earth asteroids (NEAs) and chemical analyses of fragments of asteroids (meteorites) suggest that there may be a gold mine, literally, in near-Earth space. Judged from meteorite analyses two types of asteroids offer particularly bright prospects for recovery of large quantities of precious metals (defined as Au, Pt, Ir, Os, Pd, Rh, and Ru), the ordinary LL chondrites, which contain 1.2-5.3% Fe-Ni metal containing 50-220 ppm of precious metals, and metallic asteroids, which consist almost wholly of Fe-Ni phases and contain variable amounts of precious metals up to several hundred ppm. The pulverized regolith of LL chondrite asteroids could be electromagnetically raked to separate the metallic grains. Suitable metallic asteroids could be processed in their entirety. Statistically, there should be approximately six metallic NEAs larger than 1 km in diameter that contain over 100 ppm of precious metals. Successful recovery of 400,000 tons or more of precious metals contained in the smallest and least rich of these metallic NEAs could yield products worth $ 5.1 trillion (US) at recent market prices. If marketed over 20 years, this would represent a 10-fold increase over the recent global production rate of all precious metals combined." [Kargel, 1994]

The resource and grade observations are valid but the economic approach is flawed – it ignores the fact that aggregate platinum group metal demand in 2006 was less than 20 Billion dollars (US). Injecting 400 kilotons of metal into the global economy would collapse prices, therefore invalidating the price estimate and thus reducing estimated value. Later work by Lewis [1997] amplifies this flaw by reporting a $20 Trillion (US) valuation for a metal asteroid (3554 Amun) that amounted to roughly 1/3 of the gross world product. Some members of the press who are eager for a story have recently been picking upon this theme and running with it.

"One single asteroid in our solar system - 241 Germania - has $95.8 (£60) trillion of mineral wealth inside it - nearly the same as the annual GDP of the entire WORLD." ... "The 100-mile wide 241 Germania wouldn't be a likely target for Planetary Resources, however - it's too far away, in the solar system's main asteroid belt." [Waugh, 2012]

If this continues, the result could be a loss in credibility with more level-headed members of the investing public. The problem with these estimates is that they ignore basic mining variables, including annual market size limits as well as the cost of extraction and refining.

"Several scientists not involved in the project said they were simultaneously thrilled and wary, calling the plan daring, difficult - and pricey. They don't see how it could be cost-effective, even with platinum and gold worth nearly $1,600 an ounce. An upcoming NASA mission to return just 2 ounces (60 grams) of an asteroid to Earth will cost about $1 billion. Scientists question how the company can reduce costs to the point where 'space mining' will be profitable." [Waugh, 2012]

This criticism has also been applied to lunar resources – and for good reason. Given today's high cost of space access, the resources of space are simply too costly to import. In order for this to change, a dramatic reduction must happen in launch and operations cost for today's space transportation systems. Skepticism about selling space resources in Earth's markets is justified.

"Enthusiasts for China's space programme have waxed lyrical about the vast wealth to be generated mining rare and valuable elements on the moon. But even the most ardent exponent of extra-planetary mineral exploitation must realise the idea is lunacy. Everything to do with space exploration is excruciatingly expensive. Even getting stuff to low earth orbit, a couple of hundred kilometres up, costs more than US$20,000 a kilogram. Going higher costs considerably more. By the time you've flown something to the height of GPS satellites, 20,000 kilometres up, it is quite literally worth more than its weight in gold. And the moon is 380,000 kilometres away." [Holland, 2013]

There is a simple way to flip this problem into an opportunity. The high cost of space access actually becomes one of the primary arguments for using in-situ resources – *in space*. The basic rationale for mining the moon and asteroids is that because it costs so much to launch from Earth, it should be mined locally. The value of anything, be it raw elements or a man-made construction, is far higher in space due to the investment to get it there and its scarcity in that environment. However, this added value is lost once the object is brought back to

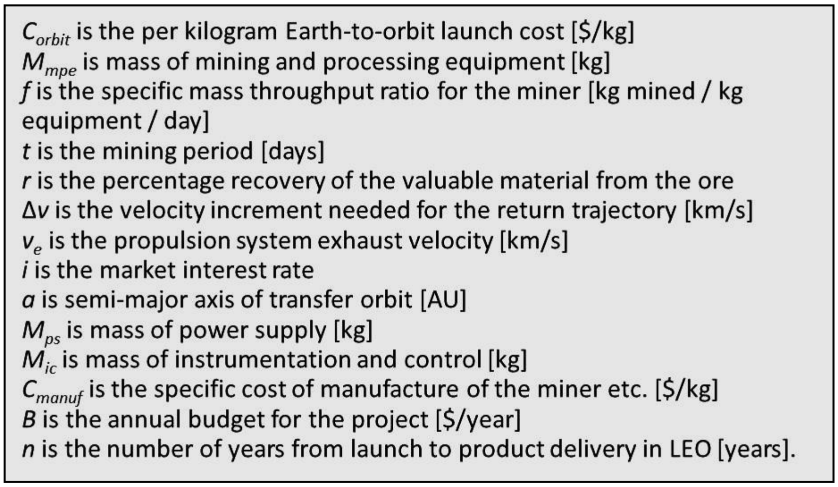
Earth. Economic projections must incorporate the loss of investment in considering whether or not to bring an object back or to leave it in space for future use. A clear example of this is water at the International Space Station, where it costs at least \$5,000 per liter to import from Earth [Greenemeier, 2006]. Exporting the same asteroid-derived water to Earth for drinking would fetch nearly \$2 per liter, reducing value by over three orders of magnitude.

"Some Near-Earth Asteroids offer very promising targets as future orebodies for in-space activities, for reasons of accessibility, ease of return, apparent variety of source materials, and probable ease of extraction of both metals and volatiles, both of which are likely to be in heavy demand during the development of large-scale space infrastructure. Such space resources will have to compete against Earth-launched resources. This may be made possible by applying the concepts of in-situ propellant production. There has been a need expressed in the literature for a general ***methodology for determining the economics and feasibility*** *of any proposed asteroid or comet mining project. This work addresses that need."* [Sonter, 1997]

The development and use of credible valuation methods for asteroid resources remains a high priority. Sonter [1997] developed an equation to estimate the present value of asteroid resources. This equation factors in several elements critical to the feasibility of asteroid use, including orbital mechanics, mining system productivity, costs and budget.

$$\boxed{\mathrm{NPV} = C_{orbit}\ M_{mpe}\ f\ t\ r\ e^{-\Delta v/v_e}\ (1+i)^{-a^{3/2}} - \ (C_{manuf}\ (M_{mpe} + M_{ps} + M_{ic})\ +\ B\ n)}$$

Where,



C_{orbit} is the per kilogram Earth-to-orbit launch cost [$/kg]
M_{mpe} is mass of mining and processing equipment [kg]
f is the specific mass throughput ratio for the miner [kg mined / kg equipment / day]
t is the mining period [days]
r is the percentage recovery of the valuable material from the ore
Δv is the velocity increment needed for the return trajectory [km/s]
v_e is the propulsion system exhaust velocity [km/s]
i is the market interest rate
a is semi-major axis of transfer orbit [AU]
M_{ps} is mass of power supply [kg]
M_{ic} is mass of instrumentation and control [kg]
C_{manuf} is the specific cost of manufacture of the miner etc. [$/kg]
B is the annual budget for the project [$/year]
n is the number of years from launch to product delivery in LEO [years].

While this is clearly a step in the right direction, Sonter's equation does not consider market size, risk or taxation – these are big issues for today's mining industry. However, due to the simplicity of the calculation, it is gaining use as a first-order approximation of value (note that mining industry standards for valuation will be covered in detail in Section 6.3). The biggest missing element in SMR valuation to date is the need to understand the marketplace or the end customer. Market information is a key factor in a credible business plan. Blair [2000] analyzed the PGM marketplace in detail, with projections about what might happen should a sudden increase in supply flood the market.

"Price could easily be driven down [by competitors] just before arrival of the first shipment, provided a marketing agreement has not been negotiated through existing sellers. The potential for space-manufactured products could insulate this somewhat (the PGM concentrate must pass through Earth orbit on its way to market). One advantage of ore refining and product manufacturing in orbit is access to high vacuum and zero gravity. The likelihood of orbital manufacturing facilities in the 20-year time frame is high, and is strongly linked with the growth required to enable asteroid mining endeavors. Specialized niche-market products that could benefit from orbital manufacturing include exotic alloys, metallic-foam based catalysts or high-purity electronic components." [Blair, 2000]

The primary reason terrestrial markets are attractive for space commodities is that they are 100% certain. Price may move around a bit; but, buyers are sure to line up. Projecting future conditions where customers must appear in space to complete the business cycle is less certain; however, it is the key to big profits for SMR.

"The ability to cost-effectively meet existing market needs is the sine qua non *of any successful space resources venture. This objective can be divided into three components. First, capital expenditures must be minimized as much as possible. Second, the time required to generate real revenues must be minimized. Third (and really a corollary of the second), real markets must currently exist for the planned products. Many proposed space ventures are* destined to fail *because their advocates have not adequately addressed these basic economic considerations."* [Gerlatch, 2005]

Figure 8. Overview of Target Markets

	Description	Addressable Market	Comments
PGMs	▪ Platinum for sale directly into terrestrial markets ▪ Other platinum group metals	▪ $5.5 billion (2003) ▪ Expect $10 billion market within 10 years	▪ Largest near-term market ▪ Main driver of mission design ▪ Huge potential growth in demand within next decade
Scientific Data/Samples	▪ Scientific data sets ▪ Scientific instruments ▪ Asteroid surface samples	▪ $100-million market ▪ Expect market to be fairly consistent year over year	▪ Space Development's experience with NEAP suggests potential ▪ Ability to deliver more results at less cost deliver a powerful value proposition
Entertainment/ Sponsorships	▪ Documentary films and videos ▪ Sponsorships and branding relationships ▪ Advertising ▪ Licensing deals	▪ Relevant segment is about $2 billion ▪ Expect market to remain fairly stable	▪ Risk associated with space activities makes sponsorships uncertain ▪ Strong public interest in space suggests potential
Orbital Use	▪ Volatiles ▪ Semiconductors ▪ Other	▪ Negligible today ▪ $100 billion orbital market within 15 to 20 years	▪ Huge longer-term market potential but requires significant infrastructure investments before it can become viable

Table 3-2 Addressable markets for asteroid resources [Gerlatch, 2005].

The single largest contributor to the cost of space access is the expendable paradigm. Capital equipment in space is manufactured for a single use – keeping costs high. The rocket equation requires exponentially more lift power the farther the destination. There is value in the perspective that this "problem" actually creates opportunity - SMR has the unique ability to linearize the rocket equation by providing a distributed set of propellant nodes in space. Valuing those transportation refueling stations as well as the mines that will support them can be done using traditional mining industry methods, including technologies, project management and finance. Indeed, some of the modeling in the Systems Analysis chapter follows a standard process of mineral project evaluation. The basic framework for valuing mining projects will be described in more detail in a later chapter.

3.4 SMR Market and Economic Assessment

This study looked at the future markets (a basic description of potential and real SMR markets) as they would be established. Much of the economic material is drawn from lessons learned in terrestrial mining and energy industries. In addition, this study group addressed multiple potential scenarios for the future against the opportunity for SMR impact. The most applicable scenario was called Civilization Boldly Advances into Space [see Appendix F].

3.4.1 Understanding the Market

Economic Feasibility Criteria

The rules of economic feasibility are straightforward: Make more money than you spend. A number of methods have been developed to account for the opportunity cost of making one choice over another in the pursuit of economic profit. These are the bread and butter of finance and management courses taught in universities today.

Opportunity Costs

The investment of resources (people, equipment, capital and time) usually has multiple paths. Once you have started down your path of choice, other opportunities are at least delayed, if not lost forever. One example is the choice of increasing production of nickel in Sudbury, Canada by 20%, or investing that money into SMR projects looking for nickel on an asteroid. The choice is the essence of the SMR revolution. To start down the SMR mining path, the opportunity costs must not only include the immediate mining capability; but, they must also incorporate the essence of the space option. Can we slow down the deletion of scare resources? Can we improve the environment by going into space mining? Will the ROI in the long-term reward the risk takers? Can we find a visionary with the financial resources needed, who understands their impact upon the future?

Mineral Economics

The mining industry translates mineral potential into the language of economics every day. In fact, the term “ore” is actually an economic term - not a geologic one. For a specific mineral assemblage to be able to qualify as “ore” it must have economic value by legal definition.

*“*Ore *is a mixture of valuable minerals and gangue minerals from which at least one of the minerals can be extracted economically. An ore body is a natural concentration of valuable material amenable to economic extraction.* By-product *is a secondary or additional product recovered in the extraction process (e.g. molybdenum is a common by-product of copper).* Mineral Reserve *is the economically mineable part of a Measured or Indicated Mineral Resource demonstrated by at least a preliminary feasibility study. This study must include adequate information on mining, processing, metallurgical, economic, and other relevant factors that demonstrate (at the time of reporting) that economic extraction can be justified. A mineral reserve includes diluting materials and allowances for losses that may occur when the material is mined.”* [Baurens, 2010]

The path from mineral discovery to active mine has many steps. Exploration and mining companies can have positive value at each stage. The chart below shows mining stage vs. value of the company for successful projects. There are failures – not all mineral prospects ultimately produce value. This is a major source of project risk.. Early steps include gathering considerable 3D geologic information using drilling, sampling and assaying methods.

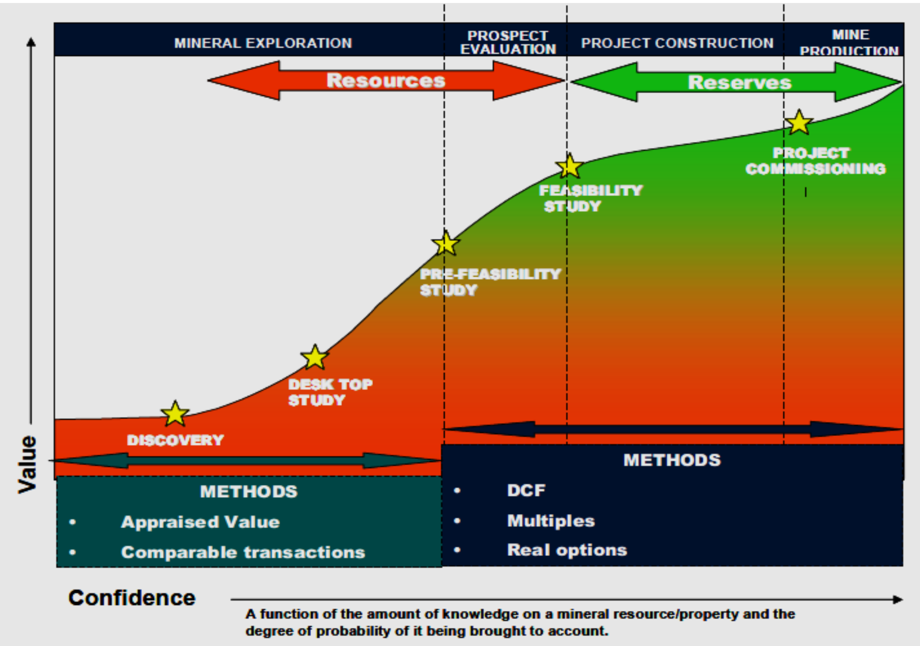


Figure 3-2, Value as a Function of Mining Stage [Baurens, 2010].

The mining industry standard valuation practice is discounted cash flow analysis for a mineral project or prospect. It is a spreadsheet predicting periodic costs and revenues for the life of the mine. Debt financing of mining projects is impossible without a credible valuation in place. Other types of valuation can include income, market and cost methods, although more esoteric methods are sometimes used to value intangible assets.

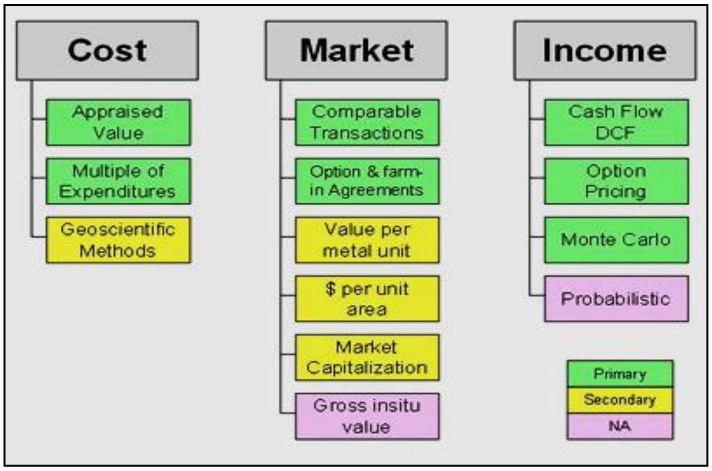
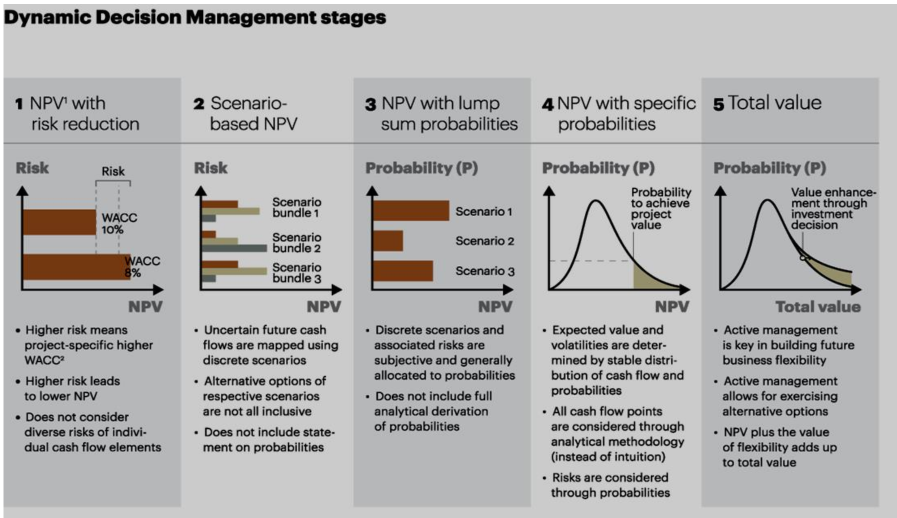


Figure 3-3, Valuation Methods used in Mining [Smith, 2009].

Time Value of Money

Metrics for estimating present value rely on a process called discounting, which is based on the belief that risky future revenues are worth less than cash in the pocket today. This process is necessary to account for other potential uses of investment – leveling the playing field in order to make good decisions. The two most common metrics for reporting valuation results both utilize discounting, and are called *return on investment* (ROI - which is a percentage of how well you did relative to a baseline), and *net present value* (NPV - which is in absolute dollar amount). A wide variety of other measurements exist, each with their own acronym; yet, they are basically derived from or related to ROI and NPV. Industry specific measures are adjusted or fine-tuned to meet the needs for particular scenarios.



- Higher risk means project-specific higher WACC²
- Higher risk leads to lower NPV
- Does not consider diverse risks of individual cash flow elements

- Uncertain future cash flows are mapped using discrete scenarios
- Alternative options of respective scenarios are not all inclusive
- Does not include statement on probabilities

- Discrete scenarios and associated risks are subjective and generally allocated to probabilities
- Does not include full analytical derivation of probabilities

- Expected value and volatilities are determined by stable distribution of cash flow and probabilities
- All cash flow points are considered through analytical methodology (instead of intuition)
- Risks are considered through probabilities

- Active management is key in building future business flexibility
- Active management allows for exercising alternative options
- NPV plus the value of flexibility adds up to total value

Figure 3-4, Adjusting NPV using Risk
and Likelihood [Freyberg, 2010].

Selection of the discount rate (alternatively known as the *cost of capital* or hurdle rate) depends upon several factors, and is generally an industry-specific preference. The discount rate is the percentage future revenues are discounted to become present values over a given time interval or study period. An averaged version called the Weighted Average Cost of Capital or WACC is often calculated to estimate the average cost of debt (short or long-term interest rates) and cost of equity (typically a function of dividend policy), modified by asset performance correlation or beta. These can vary from industry to industry; but, they form the basis for the *risk-free* cost of capital.

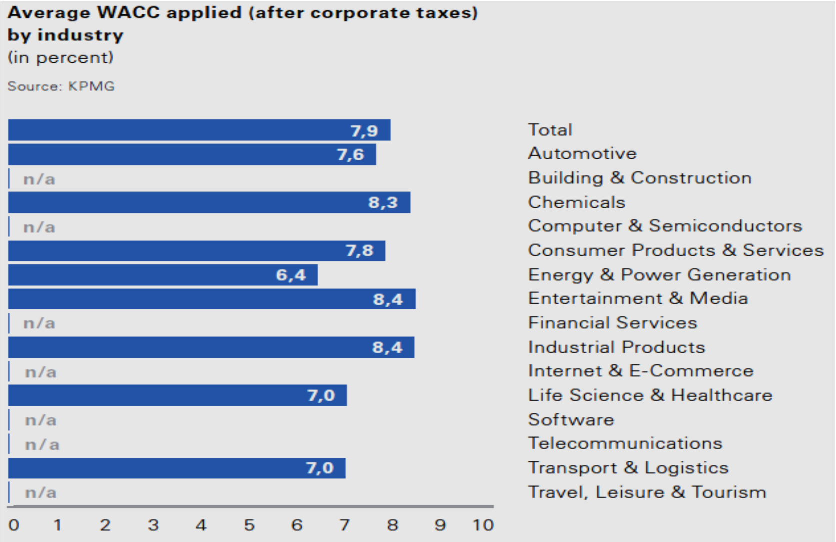


Figure 3-5, Weighted Average Cost of Capital by Industry [Elter, 2012].

Risk-adjustments are very helpful when comparing projects that have variable uncertainty with respect to each other and especially with respect to industry standards. Although it may be oversimplifying the behavior of the input causing the risk, by converting risk to a percentage discount-like adjustment factor, it creates a simple way to estimate the financial impact of that risk. Two of the greatest sources of systemic risk in mining projects today are currency risk and country risk. Adding these risk premiums to the cost of capital yields the discount rate used to estimate the NPV for a specific project. For SMR, country and currency risks would be a function of the launching nation and market as well as project risk, will likely play dominant roles. *Using these components, it is possible to calculate a project specific discount rate:*

+ Real, risk-free, long-term interest rate 2.5%
+ Mining project risk (varies with level of knowledge) 3.0%-16%
+ Country risk 0.0%-14%
= Project specific discount rate (constant dollar, 100% equity) 5.5%-32.5% [Baurens, 2010]

Resources vs. Reserves

Due to the fundamental importance of mining to the global economy, as well as the potential for abuse and distortion, international accounting standards exist for reporting mineable ore reserves. International securities law is very strict in how public companies report ore grades to the press; and, there are legal penalties for noncompliance. Rules governing reports on mining properties include the guidelines of the Australasian Joint Ore Reserves Committee (JORC), Canadian National Instrument 43-101, and the new US rules on Conflict Minerals reporting in addition to standard reporting practices covered under the US Securities and Exchange Commission (SEC). Note that until asteroids are assigned property rights and title, they must be classified as intangible assets; and, as such, they would be subject to impairment testing under International Accounting Standard (IAS) 36 and similar practices worldwide for public companies. There is a generally accepted classification scheme for that goes from inferred mineral resources through indicated and measured resources to probable reserves up to the ultimate category of economically-proven ore reserves. Clarity in the language used for resource vs. reserve reporting is what is generally required by law today.

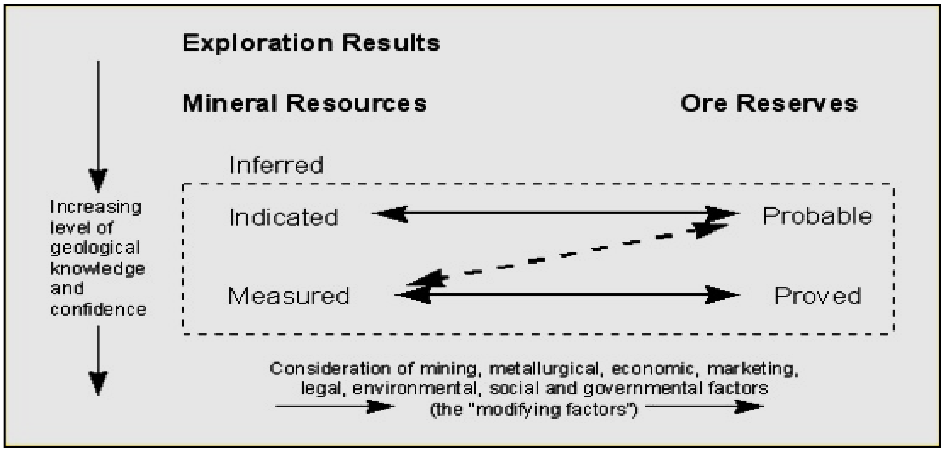


Figure 3-6, Exploration, Mineral Resources and Ore Reserves [Ramcharan, 2013].

Inferred Resource Values for SMR

Using the chart in 3-6 above, the potential for asteroid SMR value would be classified as an inferred resource. To make the transition to an indicated or measured resource, scientific data about the asteroid's geologic characteristics would have to be measured and documented. This could be proprietary, as long as an auditing agency could verify its existence and grade. A mission to do this could be as simple as multispectral imaging from a passing spacecraft; or, as complex as multiple drill holes with a sample return mission for detailed assaying. To become ore, a feasibility study would have to be completed, showing the potential for profitable sale of products into one or more existing or potential markets. This would require a mine plan with associated costs and a revenue model. Technical risk would have to be assigned to the mining and mineral processing equipment's likelihood of successfully producing ore; and, market risk would have to be assigned to the likelihood of the customer writing a check at the time of delivery. Contracts and insurance are methods of reducing market risk. Technical risk could be reduced through robust equipment testing and demonstration missions, perhaps in cooperation with an international space agency and/or with a planetary defense program.

High-Value SMR Exploration Targets

Conventional wisdom states that due to a geometric reduction in net present value, investments beyond 10-20 years are not worthy of consideration. This is especially true when higher discount rates are used for evaluation purposes. Asteroids present a unique data point in this regard. Because of the extremely high future value estimates for SMR, adjusted NPVs even using large uncertainties still yield reasonable present values. The key insight here is that even though future customers are "potential," the resource values are so high should those customers appear that it would be worth making a bet. Portfolio theory states that in order to diversify a portfolio to gain maximum returns, it is always a good idea to bet a small percentage of one's investment income in high-risk ventures. Most of the time this "risk capital" is a lost bet; but, when it is won, the payback is so big, it makes up for the other losses.

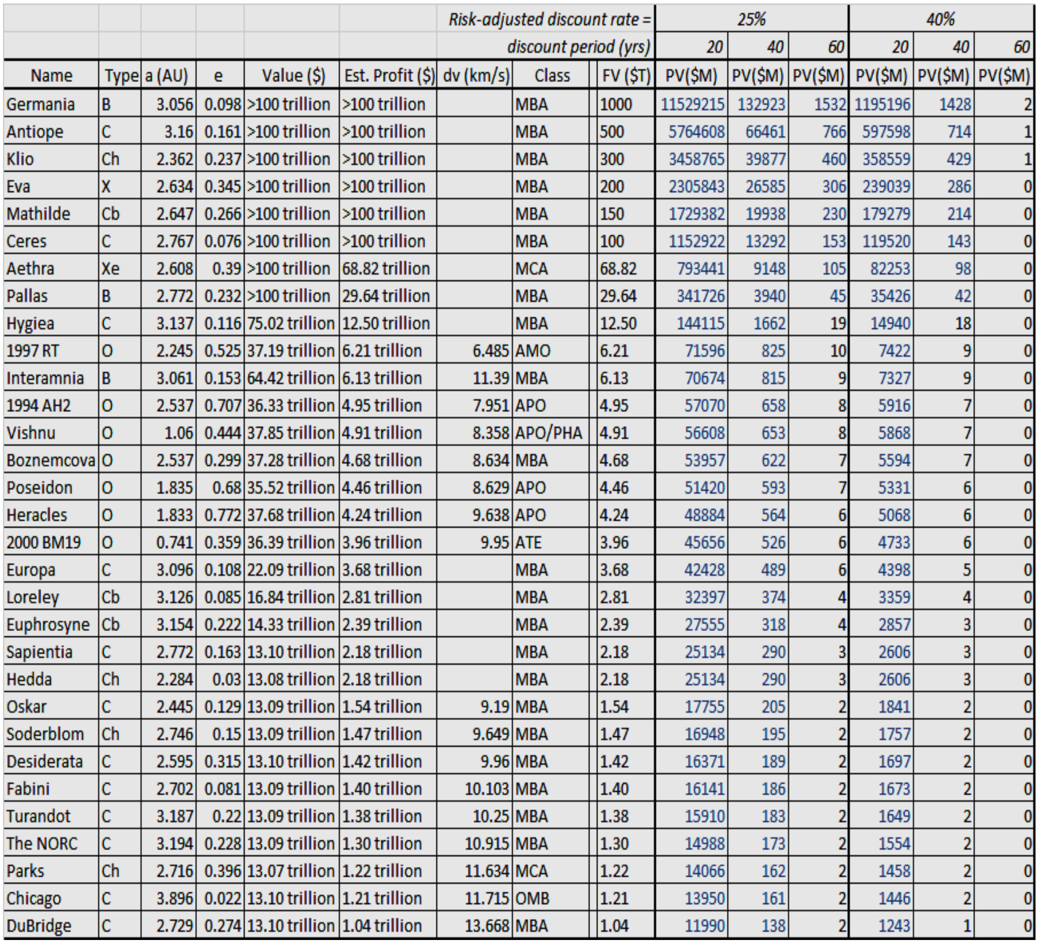
It is useful to revisit the SMR example of 3554 Amun which had a $20 Trillion (US) estimated value based on $8 Trillion (US) in precious metals (represented roughly 0.02% or 200 parts per million of the mass) with the other 99.98% of the mass estimated to be worth $12 Trillion (US) using 1997 prices for Iron, Nickel and Cobalt [Lewis, 1997]. The flawed assumption of course is that a roughly 2km sphere of stainless steel could not be introduced into the terrestrial economy without completely disrupting that economy and crashing prices. Instead, imagining an alternate reality where stainless steel could be utilized to build a future solar power satellite, cycler, starship or Gerard O'Neil space colony hull and support structure (note that this can be explicitly modeled), the in-space value would be based upon supplying the same mass from the nearest competitor – in this example Earth's surface. The cost of launching ~30 gigatons (the mass of a perfectly round 2km sphere with a specific gravity of 7.85) into an Earth-Moon cycler orbit would be over $35,000/kg (assuming it's the same as launch to GTO). Therefore, it could also be argued that the future value of Amun to a *market in space* at *some time in the future* could actually be over $100 Quadrillion (US) dollars (four orders of magnitude higher than Lewis' figure). Discounting $100Q (US) at a rate of 40% (10% for WACC and 30% for bundled risks) for 60 years yields a present value of $171 Million dollars (US). Discounting the same value at a rate of 25% (10% for WACC and 15% for bundled risks) for 90 years yields a present value of $190 Million (US). Therefore, the time value of money theory basically says that spending $171 Million today on a space mission to acquire the exclusive right to mine 3554 Amun would be a worthwhile investment (provided the market size and price scenario were estimated correctly) with a 60 year payback period at a 30% risk, or within a 90 year period at 15% total risk. This analysis can be extended to the valuation of other asteroids with the help of an online database called "Asterank" [Webster, 2013].

Name	Type	α (AU)	e	Value ($)	Est. Profit ($)	Δv (km/s)	Class
Germania	B	3.056	0.098	>100 trillion	>100 trillion		MBA
Antiope	C	3.160	0.161	>100 trillion	>100 trillion		MBA
Klio	Ch	2.362	0.237	>100 trillion	>100 trillion		MBA
Eva	X	2.634	0.345	>100 trillion	>100 trillion		MBA
Mathilde	Cb	2.647	0.266	>100 trillion	>100 trillion		MBA
Ceres	C	2.767	0.076	>100 trillion	>100 trillion		MBA
Aethra	Xe	2.608	0.390	>100 trillion	68.82 trillion		MCA

Figure 3-7 Asterank.com Automated Valuation
of Asteroid Profit [Webster, 2013].

Data on the top 30 asteroids, sorted using the "most valuable" tab, was copied into an Excel spreadsheet. These values were then discounted 20, 40 and 60 years using a 25% and 40% discount rates. Note that the first six values in the FV ($T) column are WAGs in order to extend the range of PV results, the rest are taken directly from the Est. Profit ($)

column. The results of this analysis are quite interesting and are shown below.



						Risk-adjusted discount rate =			25%			40%		
						discount period (yrs)			20	40	60	20	40	60
Name	Type	a (AU)	e	Value ($)	Est. Profit ($)	dv (km/s)	Class	FV ($T)	PV($M)	PV($M)	PV($M)	PV($M)	PV($M)	PV($M)
Germania	B	3.056	0.098	>100 trillion	>100 trillion		MBA	1000	11529215	132923	1532	1195196	1428	2
Antiope	C	3.16	0.161	>100 trillion	>100 trillion		MBA	500	5764608	66461	766	597598	714	1
Klio	Ch	2.362	0.237	>100 trillion	>100 trillion		MBA	300	3458765	39877	460	358559	429	1
Eva	X	2.634	0.345	>100 trillion	>100 trillion		MBA	200	2305843	26585	306	239039	286	0
Mathilde	Cb	2.647	0.266	>100 trillion	>100 trillion		MBA	150	1729382	19938	230	179279	214	0
Ceres	C	2.767	0.076	>100 trillion	>100 trillion		MBA	100	1152922	13292	153	119520	143	0
Aethra	Xe	2.608	0.39	>100 trillion	68.82 trillion		MCA	68.82	793441	9148	105	82253	98	0
Pallas	B	2.772	0.232	>100 trillion	29.64 trillion		MBA	29.64	341726	3940	45	35426	42	0
Hygiea	C	3.137	0.116	75.02 trillion	12.50 trillion		MBA	12.50	144115	1662	19	14940	18	0
1997 RT	O	2.245	0.525	37.19 trillion	6.21 trillion	6.485	AMO	6.21	71596	825	10	7422	9	0
Interamnia	B	3.061	0.153	64.42 trillion	6.13 trillion	11.39	MBA	6.13	70674	815	9	7327	9	0
1994 AH2	O	2.537	0.707	36.33 trillion	4.95 trillion	7.951	APO	4.95	57070	658	8	5916	7	0
Vishnu	O	1.06	0.444	37.85 trillion	4.91 trillion	8.358	APO/PHA	4.91	56608	653	8	5868	7	0
Boznemcova	O	2.537	0.299	37.28 trillion	4.68 trillion	8.634	MBA	4.68	53957	622	7	5594	7	0
Poseidon	O	1.835	0.68	35.52 trillion	4.46 trillion	8.629	APO	4.46	51420	593	7	5331	6	0
Heracles	O	1.833	0.772	37.68 trillion	4.24 trillion	9.638	APO	4.24	48884	564	6	5068	6	0
2000 BM19	O	0.741	0.359	36.39 trillion	3.96 trillion	9.95	ATE	3.96	45656	526	6	4733	6	0
Europa	C	3.096	0.108	22.09 trillion	3.68 trillion		MBA	3.68	42428	489	6	4398	5	0
Loreley	Cb	3.126	0.085	16.84 trillion	2.81 trillion		MBA	2.81	32397	374	4	3359	4	0
Euphrosyne	Cb	3.154	0.222	14.33 trillion	2.39 trillion		MBA	2.39	27555	318	4	2857	3	0
Sapientia	C	2.772	0.163	13.10 trillion	2.18 trillion		MBA	2.18	25134	290	3	2606	3	0
Hedda	Ch	2.284	0.03	13.08 trillion	2.18 trillion		MBA	2.18	25134	290	3	2606	3	0
Oskar	C	2.445	0.129	13.09 trillion	1.54 trillion	9.19	MBA	1.54	17755	205	2	1841	2	0
Soderblom	Ch	2.746	0.15	13.09 trillion	1.47 trillion	9.649	MBA	1.47	16948	195	2	1757	2	0
Desiderata	C	2.595	0.315	13.10 trillion	1.42 trillion	9.96	MBA	1.42	16371	189	2	1697	2	0
Fabini	C	2.702	0.081	13.09 trillion	1.40 trillion	10.103	MBA	1.40	16141	186	2	1673	2	0
Turandot	C	3.187	0.22	13.09 trillion	1.38 trillion	10.25	MBA	1.38	15910	183	2	1649	2	0
The NORC	C	3.194	0.228	13.09 trillion	1.30 trillion	10.915	MBA	1.30	14988	173	2	1554	2	0
Parks	Ch	2.716	0.396	13.07 trillion	1.22 trillion	11.634	MCA	1.22	14066	162	2	1458	2	0
Chicago	C	3.896	0.022	13.10 trillion	1.21 trillion	11.715	OMB	1.21	13950	161	2	1446	2	0
DuBridge	C	2.729	0.274	13.10 trillion	1.04 trillion	13.668	MBA	1.04	11990	138	2	1243	1	0

Table 3-3, Present Values Derived by Discounting Data.[MPC]

Note that values in Table 6.2 greater than $25 Million (US) have been highlighted. For the highlighted asteroids, again if all assumptions are valid, the amount worth investing in acquiring and proving the asset is shown as the PV. Another hidden assumption is that the action of exploring and tagging the SMR would create an exclusive right to mine or security of tenure – a fundamental and enabling type of property right.

Because there is currently no information available on the Asterank.com website regarding the valuation method used, all of the conjectures below depend upon the valuation assumptions and methods being valid. The table above is presented in order to show what happens when really big numbers are discounted at high rates over long periods. Provided the risk estimates are accurate (15% and 30% added to a WACC of 10%), NPVs in the millions indicate that risk capital could be gainfully spent on these high-risk ventures. Note that portfolio theory recommends always investing a little of one's investment money to cover high risk / high reward potential outcomes. The economic interpretation of this would sound something like "IF the risks are properly accounted for, and IF a multi-trillion dollar market for asteroid resources appears in the 20-40 year timeframe, it would be worth investing PV dollars today in securing the rights to such a deal." Another way to look at that is that *should the cost of a spacecraft fall below the PV threshold* for credible projections, it would be worth investing in as a private mineral exploration mission.

"Within five to seven years, the company hopes to send out a small swarm of similar spacecraft for a more detailed prospecting mission, mapping out a valuable asteroid in detail and identifying rich resource veins. They estimate such a mission will cost between $25 and 30 million." [Mann, 2012]

The next question becomes: How long would it take to create a market or grow an economy, to that size? Can this be supported by technology trends and the geometric physics of SMR? These questions deserve further research, and will form the core of the systems analysis and modeling section.

"Wired Science's resident space historian David S. Portree thinks asteroid mining might make more sense when we have a more established space-based habitats with a different economy and better technology. "Right now it would be like a big oil tanker dropping anchor off the coast of medieval England," he said. "The medieval English might identify the oil as a useful commodity, but wouldn't be able use enough to profit the tanker crew. Heck, they wouldn't know how to get it off the tanker, except in wooden pails and rowboats."" [Mann, 2012]

Careful consideration is warranted when considering 60 or 90-year discounting results. How much would a nuclear submarine be worth in 1923 dollars to the 1923 economy? How about a smartphone? Given the massive growth in the global economy in the last century, it may not be that unrealistic to consider the impossible. If global growth trends continue (for example, with the continuation of Moore's Law in one or more technology areas) large future values may indeed be reasonable and could indeed be expected.

3.5 Law and Economics - Help Drive the Market?

There is a long historic relationship between law and economics. Law is often utilized in an effort to protect capital investment and reduce the risk for private enterprise. As such, it typically follows new economic opportunities, extending a set of operating rules and principles into new frontiers or newly independent states on an as-needed basis.

Mining company preferences regarding policy and law have been studied extensively.

"Companies have many countries to choose from when deciding where to expend their exploration and development budgets. Those nations with prospective geology, reasonable tax terms, acceptable legislation and political stability have brighter prospects for long term mineral sector development than where one or more of these are absent. In analyzing investment conditions a company will apply key criteria, including tax criteria, and see how well these are met; the types of decision criteria and the weight placed on each varies from company to company." [Otto, 2007, p.9]

Results of a study on mining company preferences regarding legal regimes for newly independent states (a number of these, with substantial mineral endowments, suddenly appeared when the Berlin

Wall fell). These yielded the insights shown in Table 3-4 below. Mining companies considering investment ranked *security of tenure* (a feature of a property right – not the right itself) the number 2 decision criteria during the exploration stage, and number 1 during the mining stage.

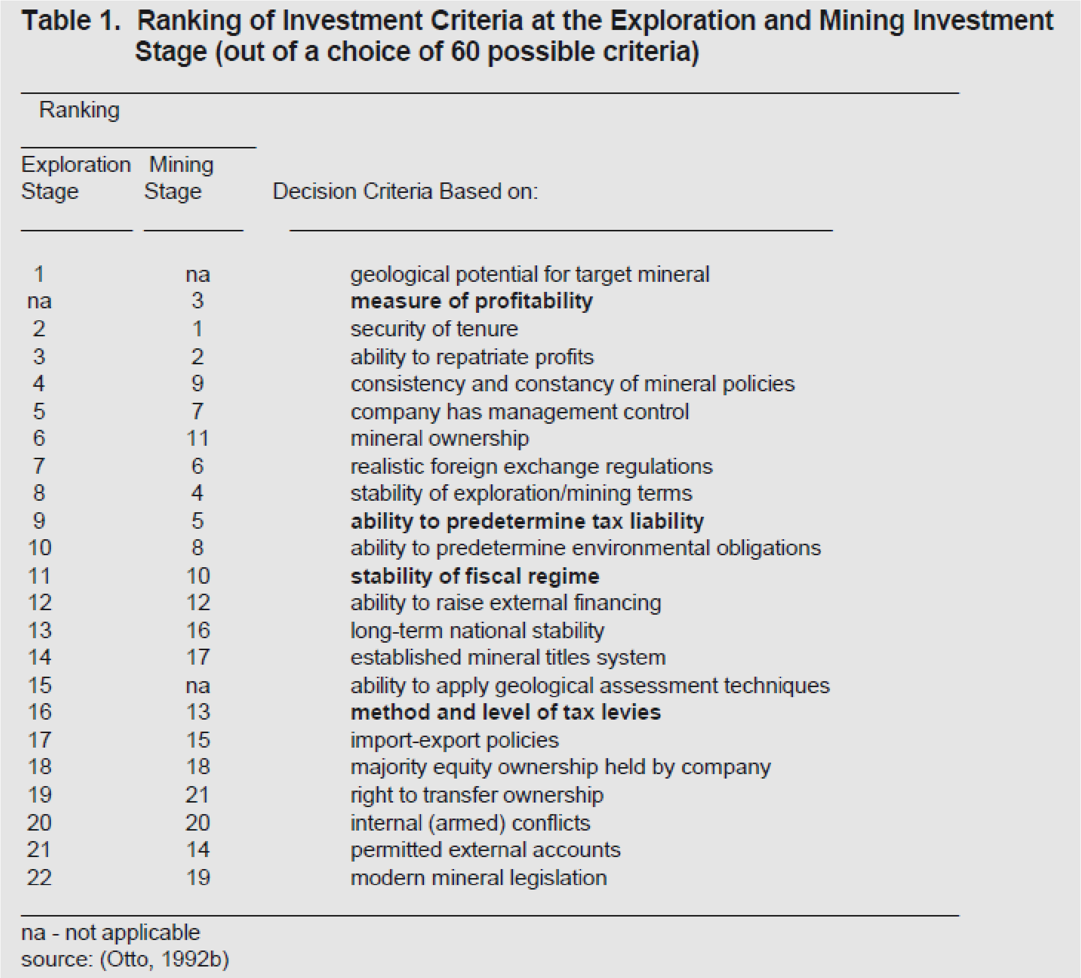


Table 1. Ranking of Investment Criteria at the Exploration and Mining Investment Stage (out of a choice of 60 possible criteria)

Ranking		
Exploration Stage	Mining Stage	Decision Criteria Based on:
1	na	geological potential for target mineral
na	3	**measure of profitability**
2	1	security of tenure
3	2	ability to repatriate profits
4	9	consistency and constancy of mineral policies
5	7	company has management control
6	11	mineral ownership
7	6	realistic foreign exchange regulations
8	4	stability of exploration/mining terms
9	5	**ability to predetermine tax liability**
10	8	ability to predetermine environmental obligations
11	10	**stability of fiscal regime**
12	12	ability to raise external financing
13	16	long-term national stability
14	17	established mineral titles system
15	na	ability to apply geological assessment techniques
16	13	**method and level of tax levies**
17	15	import-export policies
18	18	majority equity ownership held by company
19	21	right to transfer ownership
20	20	internal (armed) conflicts
21	14	permitted external accounts
22	19	modern mineral legislation

na - not applicable
source: (Otto, 1992b)

Table 3-4, Ranking of Investment Criteria [Otto, 2007, p.10].

Other important legal policy issues identified by the study included the ability to move profits across borders, predictability and stability of policies and the ability to predict taxes. Clearly, property rights are very important to mining investors. However, the right to exclusively mine an orebody has a higher priority. Note that until asteroids are given property rights, they will be classified as intangible assets, and as such would be subject to impairment testing under International Accounting Standard (IAS) 36.

3.6 Summary: SMR Market Opportunities

Primary SMR economic opportunities are intimately linked to space market maturation. By viewing markets as a function of space colonization or settlement, a feasible pathway becomes predictable and can be quantitatively modeled. Elon Musk's goal of settling Mars with 10,000 fellow humans will leave a wake trail of infrastructure and enduring enterprise. The mapping of requirements and constraints for this scenario can reveal a number of feasible SMR economic opportunities. This is the basis for the market model for the strawman on systems analysis. Basic observations about the state of the global economy in 2014 offer a context for SMR. The terrestrial economy is slowing down and capital is being sequestered (despite evidence from the past that this causes it to waste away). Economic opportunities are at an all-time low; and, attempts at stimulating the economy appear to be failing. Resource limits are becoming apparent in energy and strategic minerals, while markets are flattening with no relief in sight. A basic shift is needed in order to maintain global energy lifestyles. Space resources offer a way out, or more specifically, up. Few doubt the intensity of Elon Musk's will to set foot on Mars. Many still doubt his ability to execute that will, especially considering the cost and complexity of the required suite of craft and especially the large-scale systems integration needed to make it real. Should his dreams come to pass, many will envy what tenacity and intent built for Mr. Musk.

"There are a growing number of private sector entities that are being established to operate in this arena as well. Some of the more high-profile projects include Planetary Resources' plans to mine asteroids, the B612 Foundation Sentinel initiative to catalog asteroids, and most recently the Golden Spike Company's plans to return humans to the Moon by 2020. This is in addition to the Google Lunar X PRIZE teams and SpaceX CEO Elon Musk's goal of sending people to Mars within 10-20 years and reducing the cost of such a journey to $500,000. Musk's ultimate goal is to establish a colony on Mars supporting tens of thousands of people. He believes that at this $500k/person price point, such a colony will be

feasible and the possibilities for both public and private exploration and development of the Solar System will truly be wide open." [Pittman, 2013]

This envy is part of what drives the entrepreneurial spirit in Silicon Valley, where many others have experienced personal economic success. Many share in the desire to settle the space frontier. Risk capital is not just needed – it is actually showing up. Steering this capital toward productive returns will benefit humanity's collective future.

"The space frontier will inevitably increase the scale of thinking and risk-taking by business. When we are dealing with space, we are dealing with a technology that requires a planetary scale to stage it; decades of time to develop it; and much bigger investments to get across the threshold of economic return than is customary in business today. Business must now think in international terms, and in terms of the next business generation. It must step up to the big risks with the same vision that enabled an earlier generation of builders to push railroad tracks out across the wilderness and lay the foundations of our modern economy." [Cordiner, 1961]

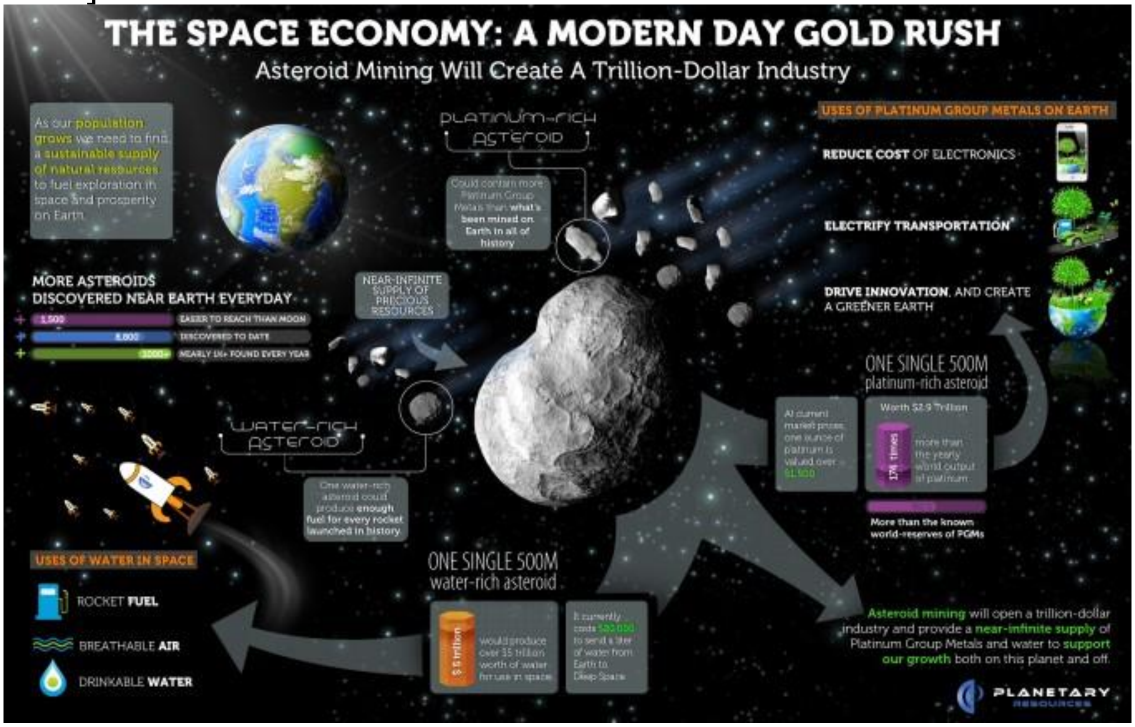


Figure 3-8, Vision of an SMR Economy

[courtesy of Planetary Resources Inc.].

Manifesting this bold vision of the future will require the collective action of government and private stakeholders. Each has an important role to play in creating a positive future, while carefully managing risks and rewards. Schumpeter's entrepreneurs disturb the equilibrium by using resources to change one or more of the 'parameters' of the economic system. However, one should not neglect the role of other agents, such as governments and international organizations, which are not limited to producing the necessary legislation for the development of the space economy. In particular, they could play an important role in the development of the space infrastructure such as space stations or planetary outposts. Furthermore, the ability of governments to support or enable long lead time technology development has been proven by NASA. Natural advantages of developing SMR technology will also accrue to countries with advanced mining and mineral refining industries, including Canada, Sweden, South Africa, China and Russia. Co-opting the help of terrestrial mining expertise into the space arena will create or feed critical experience forward into SMR technology development. Feedback loops migrating advanced technology into the mining sector are also likely, creating pathways to direct benefits back into terrestrial industry and other stakeholders. This completes a win-win loop that advances both private and public needs.

Chapter Four, ROADMAPS FOR SMR DEVELOPMENT

4.0 Introduction

"A technology roadmap is a plan that matches short-term and long-term goals with specific technology solutions to help meet them:

[1] It is a plan that applies to a new product or process, or to an emerging technology.

[2] Developing a roadmap has three major uses.

- It helps reach a consensus about a set of needs and the technologies required to satisfy those needs;
- It provides a mechanism to help forecast technology developments and
- It provides a framework to help plan and coordinate technology developments." [Wikipedia.org]

This chapter, and the remainder of the study report, will focus on the third major use. A roadmap indeed accomplishes the first two; but, this study leverages a major strength - developing structure for a program plan.

In order to "provide a framework to help plan and coordinate technological development," this chapter will set the stage with a current international governmental space exploration mission scenario and then show multiple roadmaps for commercial SMR ventures. The International Space Exploration Coordination Group (ISECG - currently hosted by the ESA Directorate of Human Space Flight) published Global Exploration Roadmaps in 2007 and 2013. The 2013 Global Exploration Strategy (GES13) lays out an excellent roadmap for international governmental collaboration for human space exploration. It offers an efficient approach to space exploration that combines resources across space agencies, reducing redundant technologies and building upon common systems and capabilities, while leveraging existing agency strengths by establishing a voluntary, international, coordination mechanism.

> *"The Global Exploration Roadmap is being developed by space agencies participating in the International Space Exploration*

> *Coordination Group (ISECG). The roadmap builds on the vision for coordinated human and robotic exploration of our solar system that was established in The Global Exploration Strategy: the Framework for Coordination (May 2007). In doing so it reflects a coordinated international effort to prepare for collaborative space exploration missions beginning with the International Space Station (ISS) and continuing to the Moon, near-Earth asteroids, and Mars. Space agencies agree that human space exploration will be most successful as an international endeavour, given the challenges of these missions. Agencies also agree that pursuing this endeavour will deliver significant social, intellectual and economic benefits to people on Earth. This document presents the status of the space agency exploration road mapping activity. By sharing the results of this work with the broader community, space agencies seek to generate innovative ideas and solutions for meeting the challenges ahead."* [ISECG, 2013, p.3]

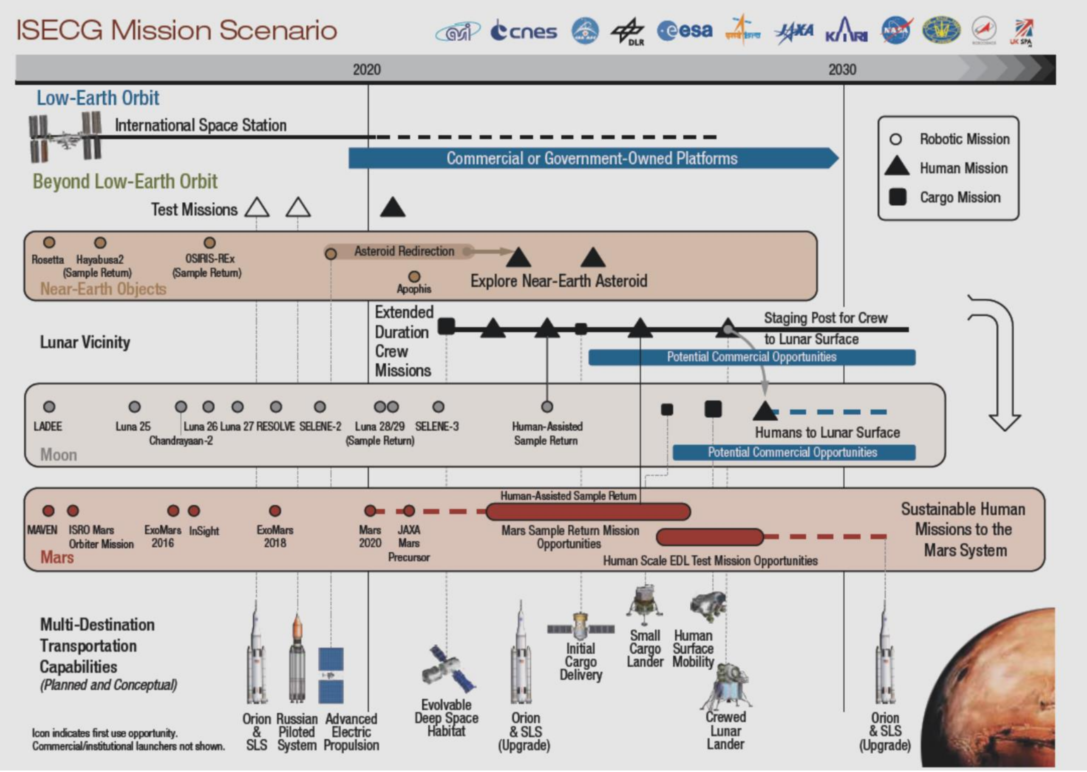


Figure 4-1. Roadmap Scenarios– Moon, Mars and Asteroid[ISECG, 2013].

However, the international framework does not address opportunities for independent commercial ventures. Obviously, the companies discussed in the first part of Chapter 3 will be active in moving beyond LEO while Elon Musk has a vision of 10,000 humans on Mars within his lifetime. Commercial space endeavors must be shown in a similar format illustrating the strengths of the commercial approach to exploration and SMR ventures. One commercial opportunity could be a refueling station at EML-1 selling water, oxygen, hydrogen, and fuel.

4.1 Framework Development:

The framework development process developed by Technology, Architectures, and Integration; LLC (President Michael Fitzgerald) is used. A quick look at the development of a roadmap will illustrate the logic inherent in the process and the results. The process is well known in the space community; and, it is leveraged quite often when establishing or improving an architecture (such as adding to a weather satellite constellation). One of the first steps is to look at a SMR commercial venture as a system of systems that must be visualized as a logical layout of systems, subsystems, components and parts. An example was chosen to show a SMR commercial venture to develop a small part of the total SMR roadmap, the systems engineering segment. The first step was to breakout the total project into segments, such as propulsion (getting off Earth and in orbit), mining, storage, and recovery. The systems engineering segment is just one of many parts of the SMR architecture. The breakout of the roadmap segments usually parallels the traditional work breakdown structure. The next few figures will show how the team progressed from looking at the systems engineering segment that broadened into a roadmap with major steps to be accomplished within a pre-determined schedule. When dealing with a major technological project in space, the philosophy has always been test, test, and then test some more. This series of demonstrations was historically driven by the fact that we do not have a 20,000 km screwdriver when something fails in space. The initial tests are small demo's of subsystems, leading to larger systems with more strenuous testing. The final test is usually a full-up operational satellite in a thermal vacuum chamber. However, as SMR projects must work many tens of thousands of miles from Earth, there will probably be a final, full-up systems test in the LEO arena preparing for departure of SMR hardware. The first chart shows the segment breakout for the SMR mission to an asteroid. The segments are: systems engineering, launch & propulsion, spacecraft, SMR processing, and headquarters/principle operations center.

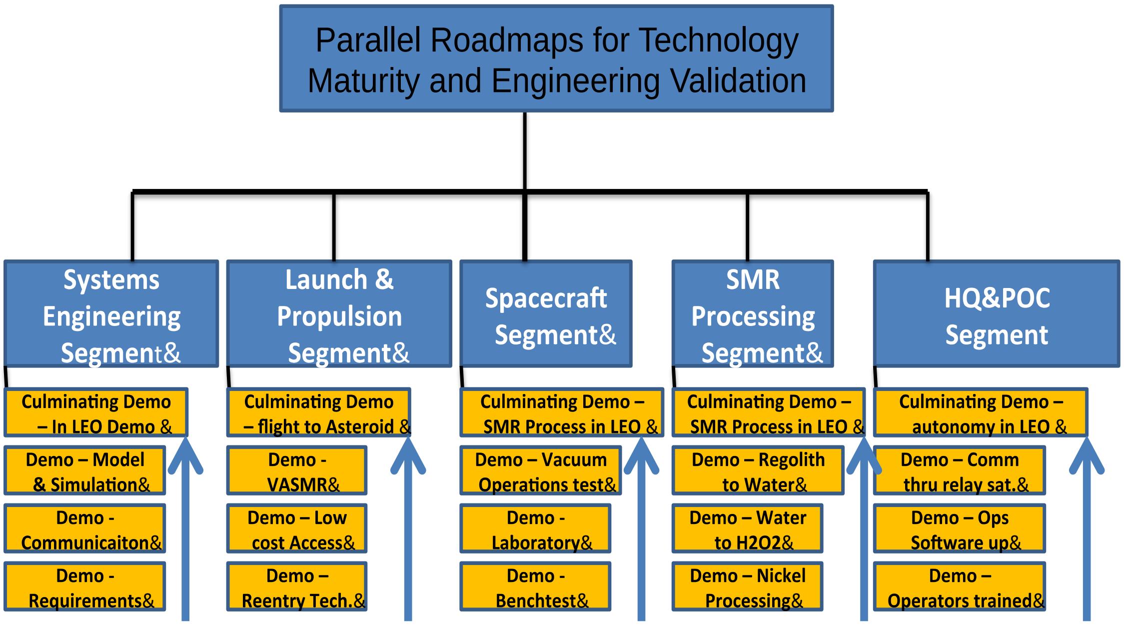


Figure 4-2, Roadmap Segment Breakout [image by TAI]

Underneath each segment is a layout of the demonstrations that must be completed before moving to each culminating demonstration. This layout of a work breakdown structure (WBS) [or a segment by segment view] is illustrative as it is missing critical topics. However, by keeping it simple, with only five segments, the idea is more easily portrayed. The next figure shows a simple rotation of the segments so that the big picture can emerge.

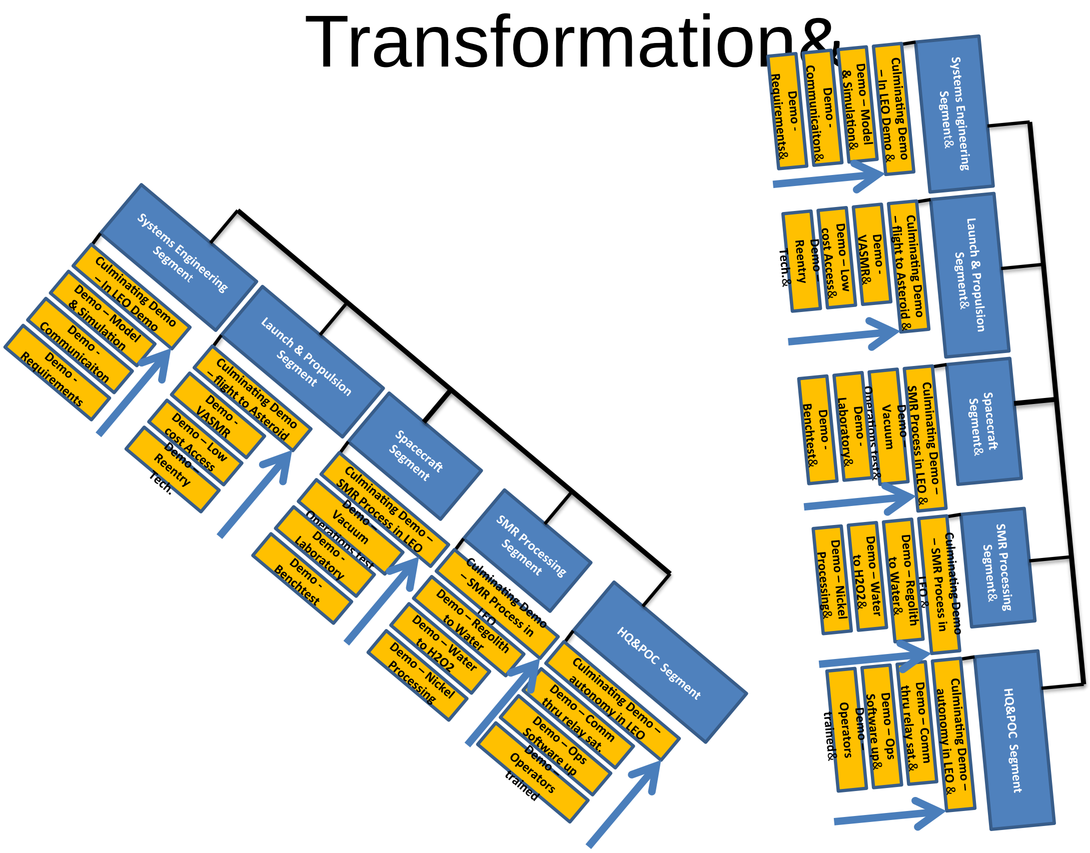


Figure 4-3, Roadmap Transformation [image by TAI]

The final sample roadmap figure is the "big picture" of the systems engineering segment of the SMR architecture. Figure 4-4 shows the layout for the systems engineering segment with critical demonstrations flowing from left to right. A scheduling format can then be easily laid out by identifying the start date, end date, and duration of each risk reduction, technology development demonstration. This would then naturally lead to a roadmap for the development of a SMR architecture. It shows interfaces with other segments as well as the need to develop implementation plans for major functions of the system engineering discipline. As the flow has demonstrated, the tests build up until the grand challenge is successfully achieved in LEO. Thus proving that a SMR architecture would lead to a successful commercial venture.

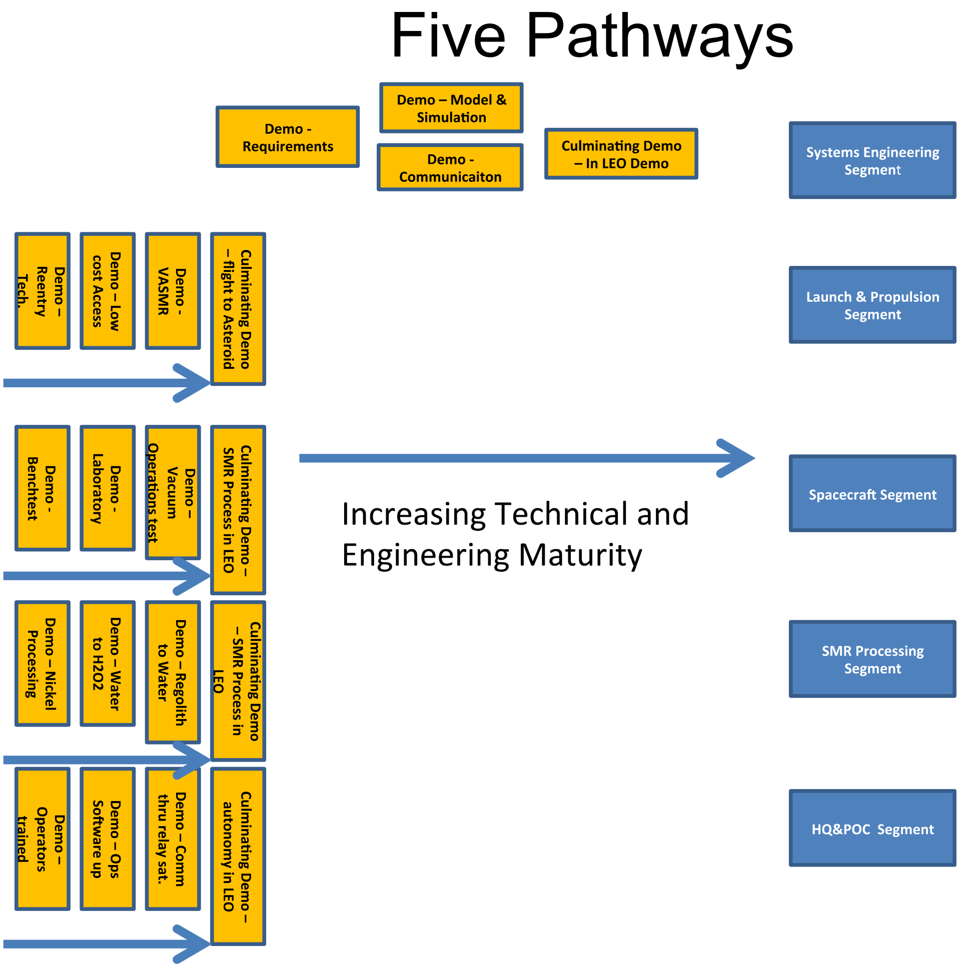


Figure 4-4, SMR Roadmap Pathways [image by TAI]

The last figure in this series shows the complex layout of a serious roadmap for a segment of the SMR architecture. This image shows the major aspects of the roadmap and how they interact with each other for the systems engineering segment.

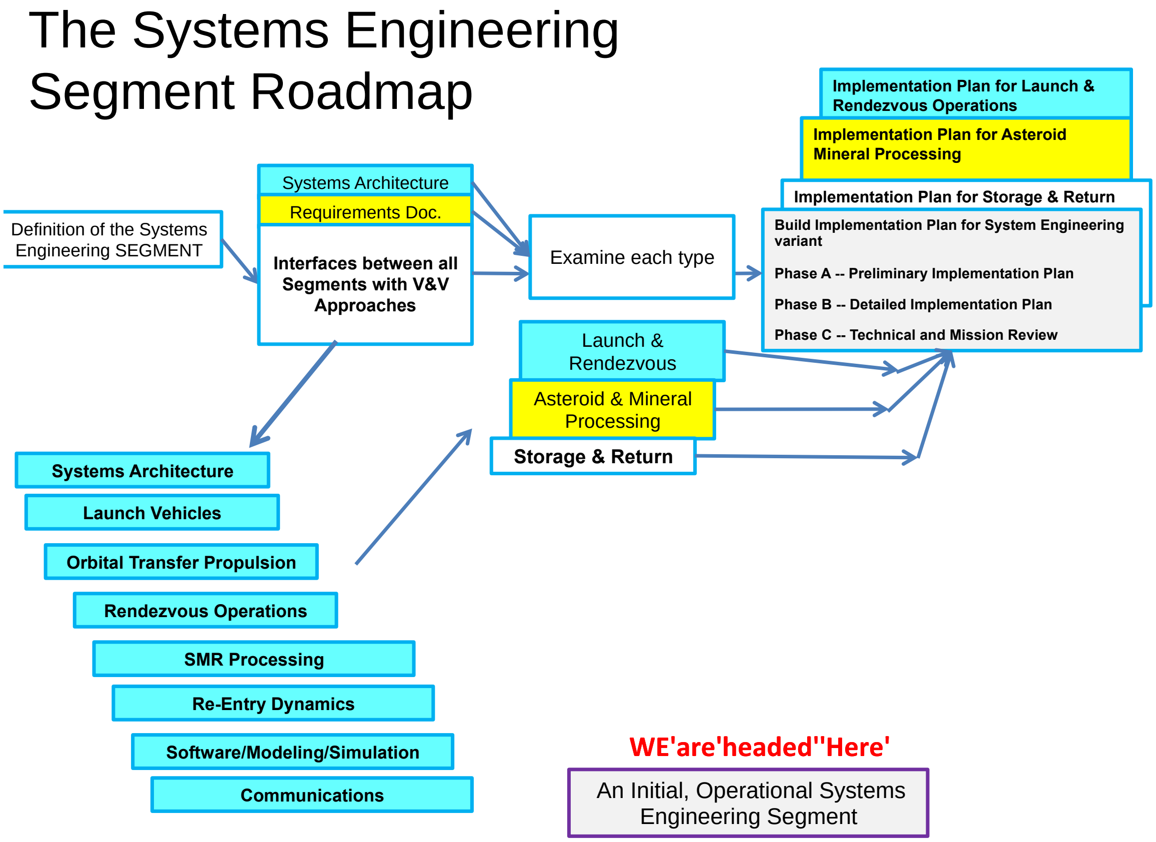


Figure 4-5, Major Roadmap Layout [image by TAI]

Once the layout of the roadmap has been accomplished for each of the segments, the next step is to identify the sequence of test or demonstrations required. They usually break down into:

Technical Feasibility: these are the first demonstrations that start in small scale and build to subsystems or system levels. These could be achieved by simulation or identification as well as physical testing. The next image shows this initial step.

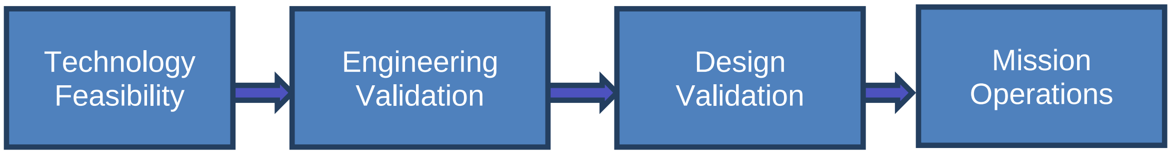


Figure 4-6, Sequence of Testing [image by TAI]

Engineering Validity: The next set of demonstrations illustrate engineering solutions that mitigation risk arenas.

Design Validity: This is the last step of demonstrations or testings inside each segment leading to Grand Challenges.

Mission Operations: This is the "proof-test" that everything is working as planned. The difficulty with space projects is that there is very little opportunity to "fix" the system after insertion into space.

4.2 SMR Roadmaps:

The following sections will expand upon each roadmap illustrating the steps, or phases, to eventually produce profitable SMR ventures to the Moon, Mars, and especially, asteroids. The information was gained from each of the companies as well as directly off their website. The examples are:

- Deep Space Industries with near term expectations
- Planetary Resources with their aggressive asteroid approach
- Shackleton Energy Company with water delivery
- Excalibur Exploration with three phases of development

4.2.1 Deep Space Industries (DSI)[4]:

Deep Space Industries was formed in 2013 as a Delaware corporation and is headquartered (as of October 2014) in Austin, Texas, with a spacecraft design/construction shop located at the NASA Ames Research Park in California. Deep Space Industries is a renaissance company, with leaders from space commerce, policy, asteroid missions, technology development, and risk management. The current revolution in commercial space – from the creation of NASA's program funding SpaceX, Boeing, and Orbital Sciences to the X Prize and private travelers on the International Space Station – flow in part from the ground work laid by DSI founders. The Company's leadership also includes the project manager of NASA's current robotic mission cruising through the main belt asteroids beyond Mars, and an executive who ran NASA's $850 million space technology development program. Developing a profitable asteroid prospecting and selection strategy demands the

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[4] Note: most of the material in each of the corporate sections is either quoted or heavily paraphrased as a way to capture correctly the intent of the commercial company.

world's most knowledgeable experts. Deep Space benefits from the leadership of Dr. John Lewis, whose research led him to write the most influential books on asteroids as both resources and threats.

Goals and Vision

The Deep Space Vision: To enable the expansion of the human race into the space frontier by developing the ability to live off of and profit from the harvest of space resources.

The Deep Space Mission: Deep Space Industries will change the economic model of doing business in space by providing the technical resources, capabilities and system integration required to discover, harvest, process and market in-space resources.

Our Business: While focused on the long-term provision of services and supplies in space, Deep Space is currently providing technologies and services for the commercial government space sectors while developing both new technologies for use in space and synergistic terrestrial retail and media activities.

Approach

The Deep Space approach to space mineral resources has multiple phases, but essentially starts with a very good awareness of the situation, conducts some prospecting with smaller spacecraft, acquires some minerals for processing, processes minerals, and then sells them to operational space activities as "in-orbit assets."

Situation Awareness: The most valuable near Earth asteroids (NEAs) are those whose orbits closely mimic that of Earth, so that minimal energy is required to reach them and return. More than two million are estimated to exist, yet only 11,300 have been charted. The list of known NEAs grows by about 1100 each year; but, it will likely accelerate as additional resources are brought to bear on the task. NEAs are a plentiful resource and the availability of affordable-to-reach targets will continue to expand.

Prospecting: Because only 11,300 of the estimated more than two million NEAs have had their trajectories charted, an important element of prospecting will be the identification of the as-yet-unseen millions of potentially valuable objects. The vast majority of the 11,300 have been seen only as single pixels, ensuring that little is known about the tiny few that have been found, including their true size. Next steps therefore include both finding more NEAs and finding out more about them than just their trajectory. NEAs are diverse objects. Some are matter from the dawn of the solar system that was never gathered up into a planet or moon (called "unconsolidated" NEAs). Others are fragments of bodies that did coalesce and condense, but broke apart. These can have a range of compositions and mineral types. Extinct comets that are half ice also are believed to lurk among NEAs. Different markets will be best served by specific types of NEAs, making prospecting imperative. Some data can be gathered telescopically, especially if paired with infrared observations. In many cases; however, NEAs as seen from Earth are very dim and yield little insight on their composition. This makes on-site robotic inspection of NEAs a key task. Return of samples to Earth for detailed analysis would be the final step in the prospecting process.

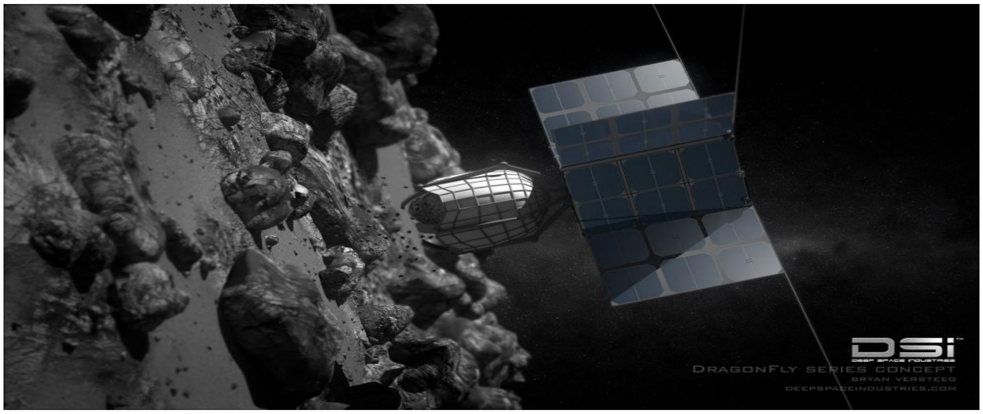
Material Acquisition: Space miners can acquire asteroid ore and process it on site, shipping out only the refined components, or they can transport raw or beneficiated ore to stable locations near or on Earth for processing. Both approaches may make sense for particular applications in various situations. On-site processing saves transportation costs by shipping only the valuable portion of the NEA. The challenge is that NEAs have low-energy near-Earth approaches infrequently, so the wait between placing processing equipment on an NEA and its next close pass when products can be shipped can be ten, twenty or even fifty years. Many more NEAs and their orbits need to be charted to see if on-site processing can be accomplished in time periods that make economic sense.

The alternative is to move raw asteroidal material into a parking orbit near Earth or directly to Earth, either by moving an entire small NEA (one to ten meters diameter) or by collecting parts of a larger NEA and delivering that subsample. Small NEAs, by their very nature, are difficult to spot from Earth, and hard to acquire and track by spacecraft sent out to find them in the vastness of interplanetary space. Medium to large NEAs are easier to spot and track by approaching spacecraft. Some, such as Itokawa, are littered with boulders that presumably could be collected and delivered back to an Earth orbit. Others appear relatively smooth and may require some means to acquire a subsample – shearing, shattering or drilling to create a piece of the right size for transport. Alternatively, spacecraft could focus on collecting just the already-shattered regolith from the surface and near subsurface.

<u>Processing:</u> The two primary materials of value expected from asteroids are volatiles and nickel-iron mixtures. Volatiles will be comprised of many elements and compounds (water, ammonia, carbon monoxide and kerogen are expected to be abundant). In addition to nickel-iron (natural stainless steel), much smaller amounts of precious metals are expected. Asteroid processing likely will begin with a subset of processing steps to extract the elements or compounds with the highest immediate value. The residue of these initial processes may be stored until demand for them increases, or less-expensive ways to unlock them are perfected. Material left over after the majority is processed into high-value outputs still has value for the in-space market as radiation shielding.

DSI Technologies:

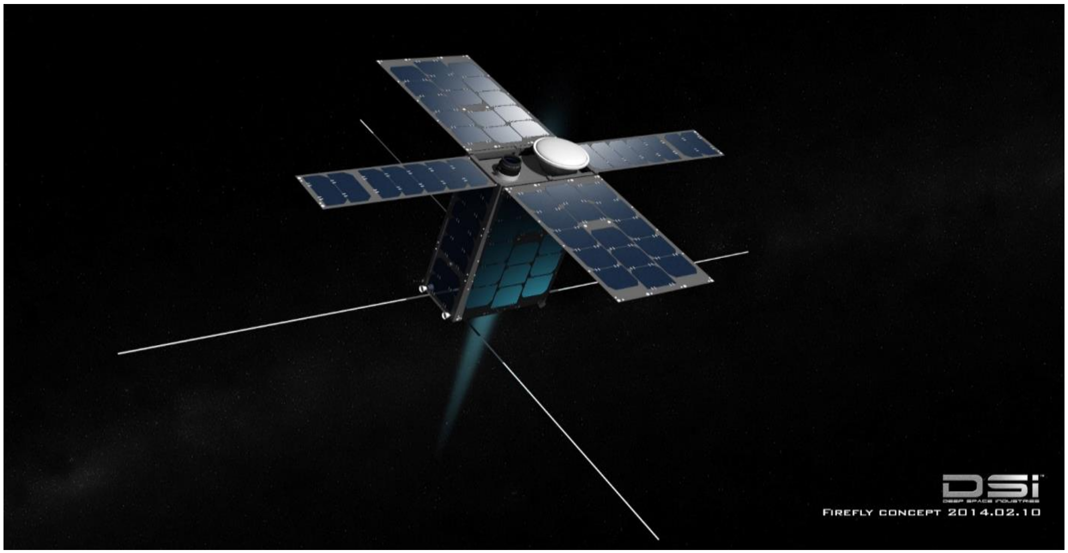
The Deep Space Industries prospecting agenda begins with one-way FireFly spacecraft that rendezvous with candidate asteroids. FireFlies are launched as secondary payloads into GTO or GEO orbits, and then use their own ion propulsion to depart for their targets. FireFlies utilize the six-unit (6U) CubeSat form factor and much of the components are available at very low cost for LEO CubeSats. To these, Deep Space adds more capable communications and propulsion able to deliver multiple km/s of deltaV. Another key addition is the FlareGuard system for dealing with interplanetary radiation. Constant dose rates in interplanetary space are survivable for carefully screened commercial space components, but sudden solar events usually are not. FlareGuard watches for the rise of solar event particles and turns off most components so they are not harmed during the flare. Once the danger has passed, the system restarts. Other Deep Space prospecting craft include the DragonFly (for returning 5 to 15 kg of samples from an asteroid), the Mothership of Asteroid CubeSats. DragonFly trajectories have been calculated that enable round trip transits lasting only two or three years (within the limits that carefully selected commercial space components can be expected to survive in deep space). Samples would be returned to the Earth's surface so that Deep Space Industries can carry out detailed analyses of how its processing technologies would handle raw asteroidal material. (While meteorites can be used as analogs for asteroid content, very few of the softest high-volatile grades of carbonaceous chondrites survive atmospheric entry; and, the ones that do are not available for destructive testing.)



DragonFly spacecraft will collect 5 to 15 kg samples from candidate asteroids and return them to Earth for detailed analysis of suitability for processing into products

Figure 4-7, DragonFly [DSI]
Figure 4-8, FireFly [DSI]

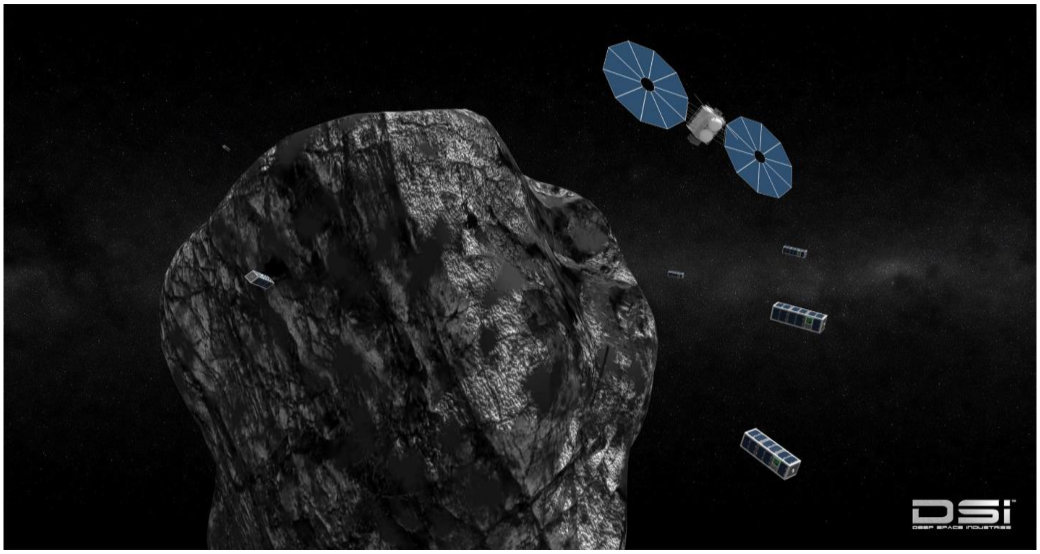
The Mothership of Asteroid CubeSats is designed to enable broad



The FireFly prospecting spacecraft from Deep Space Industries will characterize potential candidates for asteroid harvesting activities through on-site inspection.

Credit: Deep Space Industries

participation by the scientific community interested in small bodies by delivering third-party experiments and sensors to a NEA. The Mothership service includes delivery of nanosats built by a variety of researchers, communications relay to Earth, and video of the asteroid surface and surrounding area. This service allows researchers to house their instruments in a low-cost nanosat body that does not require the high-performance propulsion or deep space communications capabilities that otherwise would be required for an asteroid mission. The Mothership would be designed to carry a variety of form factors, from chipsats to 1U to 8U CubeSats.



The Mothership of Asteroid CubeSats will deliver approximately a dozen nanosats averaging three units (3U) in size, providing deep space communications for independent sensor payloads from diverse researchers.

Figure 4-9, Mothership [DSI]

The MotherShip offers rides to the vicinity of NEAs for extremely low relative costs. Space IS available!

Credit for figures 4-7, 8, 9, & 10: Deep Space Industries

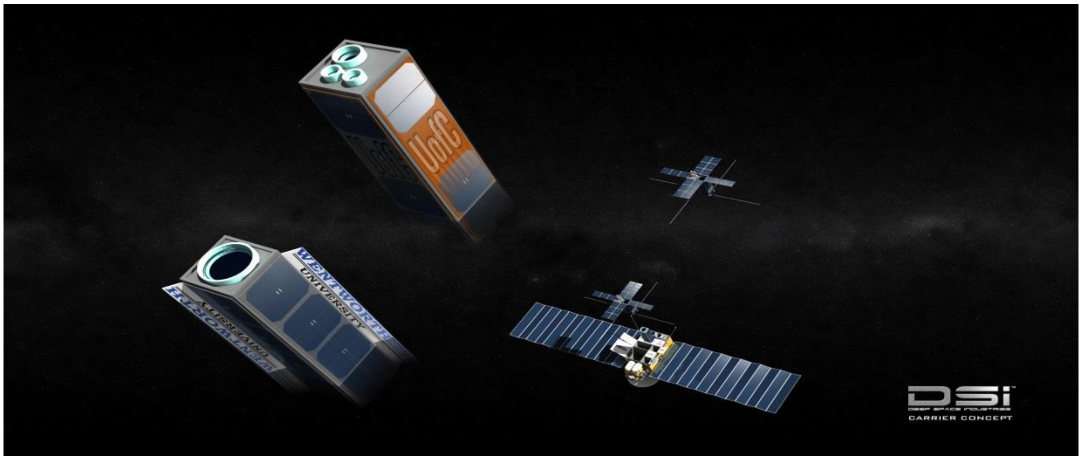


Figure 4-10, DSI Satellites

4.2.2 Planetary Resources:

Much of this section is paraphrased or copied from their website. [planetaryresurces.com] Planetary Resources is bringing the natural resources of space within humanity's economic sphere of influence, propelling us into the 21st century and beyond…today. Asteroids will play a key role in the development of a space economy and be the main driver in allowing humanity to become a flourishing multi-planetary species. Water from asteroids will fuel the in-space economy and habitation, by creating rocket fuel and consumable water from space, for space. Rare metals will increase Earth's GDP when mined from asteroids in our Solar System – the very same objects that brought them to Earth in the first place.

VISION: Our long-term vision is nothing less than expanding humanity's resource base and extending the economy into the Solar System. Asteroids are the target to achieve this, by mining high concentrations of water and precious metals from the Near-Earth asteroids and delivering these resources to their point of need for an economic return.

Approach:

We've been mining asteroids on Earth for centuries.
Planetary Resources is going to the source.

Some of Earth's richest ore deposits (such as Canada's Sudbury Basin) can trace their origins to ancient asteroid impacts. By going to the orbital source, Planetary Resources can harvest platinum group metals in much higher concentrations than even the richest Earth mines. A single platinum-rich 500 meter wide asteroid contains about 174 times the yearly world output of platinum, and 1.5 times the known world-reserves of platinum group metals (ruthenium, rhodium, palladium, osmium, iridium, and platinum). This amount is enough to fill a basketball court to four times the height of the rim. By contrast, all of the platinum group metals mined to date in history would not reach waist-high on that same basketball court.

While platinum group metals are enriched in asteroids to often hundreds of times that of the richest mines on Earth, they still represent just a small fraction of the total mass of an asteroid. Extraction processes could be chemically or energy intensive, requiring abundant solar energy, fuel, working fluids, and machinery. An abundant, cheap, local source of fuel and working fluids are a natural building block towards developing space metal mining capabilities and then delivering those resources back to Earth.

Why Asteroids? Earth is finite, but our economic growth need not be. Asteroids will fuel a mass-constrained economy in orbit and back on Earth. In orbit, spacecraft propellant is a multi-billion dollar industry with each pound of fuel worth more than an equivalent pound of gold on Earth. Certain asteroids are loaded with hydrogen and oxygen, the components of rocket fuel. These asteroids can provide a fuel source that is 100 times closer energetically to Earth orbit, and thus far less expensive, than the Apollo-Era "bring-everything-with-you" propellant used today. Back on Earth, platinum group metals are necessary for everything from catalytic converters to jewelry to the construction of electronics, medical devices, glass, and turbine blades. Despite their high price tags, these metals are used to manufacture one in four goods that we use every day. Today, the major sources of platinum group metals are concentrated in South Africa and Russia, and becoming increasingly hard to access over time. But in space, a single 500-meter platinum-rich asteroid contains more platinum than has been mined in the history of humanity. Planetary Resources is building the technology to access these resources today.

Initial Target: Water is the fuel, shelter, and sustenance of space. Every frontier expansion and gold rush in history relied on a local source of energy and a transportation backbone. Space will be no different. Before mining precious metals, Planetary Resources intends to produce fuel in space from carbonaceous chondrites rich in water that can be broken down into highly efficient LOX/H2 rocket fuel. Rocket Fuel is an attractive early resource for several reasons:

1. A large market for fuel in space already exists.
2. Fuel will open the interplanetary equivalent of exploration era trade routes.
3. Fuel enables other resource mining operations in the future.
4. Mining in space is different than mining on Earth, and in some cases, it may be simpler.

The actual method used for extracting and refining rocket fuels from asteroids will depend upon the specific composition of the target asteroid and will require an up-close investigation with Planetary Resources's ARKYD prospectors. However, the mining equipment required may be simpler than you imagine. In some cases, much of the equipment we need to mine on Earth (drills, excavators, concentrators) may not be required. Even surface contact with the asteroid may not be necessary due to the unique environment of space. One possible concept for extracting water from an asteroid may be as follows:

1. Enclose: Fully enclose a small asteroid or position a cold plate in the vicinity of a large asteroid.
2. Heat: Concentrate and direct freely-available thermal energy from the sun onto the asteroid. At temperature, water will volatilize similar to what occurs naturally with approaching comets. The gaseous water will freeze on contact with the cold plate in a largely pre-concentrated form.
3. Release: Once the desired quantities are captured, release or depart from the asteroid to deliver the fuel to the point of need, in Earth orbit, or elsewhere in the Solar System.

Many of the engineering systems required for such a process have already been demonstrated in space. But before they can be deployed to mine asteroids, we must first learn which asteroids are rich in water and how that water is locked within the asteroid. Without advances in this knowledge, the engineering and deployment of water-harvesting spacecraft would be excessively risky.

Why now? It wasn't possible until today. Every gold rush, land grab and resource-driven economic expansion started with a discovery and followed with the development of technologies to access these discoveries. Nine out of ten near Earth asteroids have been discovered since the year 2000. In the past decade, governments have invested billions to visit, survey, and successfully return resources from asteroids. In that time, Planetary Resources has identified specific targets of great interest and promise, and has begun the development of the technology that will allow humanity to harness these resources.

Game Plan:

Planetary Resources is developing a spacecraft control architecture that is both modular and upgradable, right from the beginning. This investment supports the rapid deployment and evolution of our spacecraft as internal and external demands change. This includes many innovative approaches which will enable faster delivery to orbit of hardware designed for mining space resources and supporting Earth based missions. A few of the concepts are:

<u>Vertically Integrated:</u> With spacecraft control, you are only as good as your hardware. And in some cases, the right sensor or actuator for this critical function may not be available or cost-effective. That's why we have built a new suite of sensors and actuators right here at Planetary Resources. These systems can measure a spacecraft rotating at a rate slower than the hour hand of a clock while pointing a beam within the width of a dime one mile away. By controlling the design of both the components and the system, we can balance capabilities and risks where they are appropriately taken rather than depend upon historical vendor decisions. And when the time is right to upgrade, we control our own path.

<u>Instinctive Control:</u> Controlling spacecraft attitude is inherently a system level function. This has driven us to reimagine how the role of attitude determination and command system (ADCS) is distributed within a spacecraft. We have moved away from a traditional, centralized

approach in which a single compute element is responsible for the ADCS system and have instead adopted the idea of basic, instinctual behaviors. Instincts are a way of commanding and protecting critical spacecraft components locally, using an integrated and distributed network of low-level hardened compute elements. Similar to a person instinctively removing their hand from a hot surface, the ADCS system has built-in instinctual responses that react to protect the system without relying on the central brain.

Laser Comm's: Planetary Resources has found a solution to this problem in the form of optical communications. Due to the shorter wavelength of optical communications when compared to RF, lasers allow for information to be communicated through a more tightly controlled beam using a significantly smaller aperture. This narrower focus greatly reduces the power required for a given communications data rate and distance, allowing a small spacecraft to effectively relay scientific and technical data, even when it is on the other side of the Solar System. Planetary Resources is developing a multi-function main instrument for its Arkyd spacecraft platform, one that integrates remote imaging, optical navigation, and optical communications into a single, resource-efficient tool.

Ride Sharing: Sending a spacecraft into deep space is an energetically expensive proposition. Conventionally, a spacecraft headed out into the Solar System would be placed directly on its outbound trajectory by its own launch vehicle. This launch vehicle alone can be a $100 Million proposition, or more. We are taking a different path. Our Arkyd prospecting spacecraft are small enough to hitch a ride into space with larger, primary payloads. We launch one at a time into an orbit based upon the needs of the rocket's primary payload.

Specialized Systems: Asteroid prospecting requires tools that can determine mineralogy, water composition, macroporosity, and other ore body characteristics. We are developing sensors that operate over a wide spectral range beyond traditional visible wavelength sensors to achieve these goals. When combined with Planetary Resource's agile small spacecraft platform, these sensors also have major applications closer to home: Earth Observation and Space Situational Awareness.

H_20 will open up a trillion dollar market in Space: The present day space economy spends billions of dollars on rocket fuel each year to propel spacecraft into their final orbits and to keep those spacecraft safely in their positions. Water from asteroids can be broken down into Hydrogen and Oxygen-based rocket fuels in order to meet this growing demand. Strategically placed re-fueling stations can triple the up-mass of GEO-stationary orbit bound rockets, extend the life of telecommunications satellites, and remove hazardous space debris all for a small fraction of current costs. And water is more than the "oil of space." In orbit and beyond, water plays a critical role hydrating astronauts, providing oxygen for life support, and serving as a shield against harmful radiation in space.

<u>ARKYD Space System:</u> Every mine starts with a geologist exploring on horseback. Our geologists and horses just happen to be robots. Asteroid mining activities must be preceded by the development of asteroid prospecting capabilities. The ideal prospector craft is capable of rendezvousing with an asteroid, surveying the surface for weeks at a time, and then landing or impacting to conduct in-situ measurements. NASA and the Japanese Space Agency have demonstrated these capabilities; but, they required multi-hundred-million-dollar budgets and time frames of a decade to do so. Planetary Resources is standing on their shoulders to perform commercial prospecting at costs that are more than an order of magnitude less.

<u>Test Vehicles:</u> Software programmers release versions and beta-test. Space hardware doesn't need to be any different. With the small size, and low cost of our spacecraft hardware, Planetary Resources is using space as its test bed. Beginning in Earth orbit, we are deploying a series of increasingly more capable spacecraft, allowing for research and development, iteration and test.

Our first spacecraft, the ARKYD 3 and ARKYD 6, are testing and progressing our newly developed core technologies for low-cost deep space exploration. These test missions lead into the ARKYD 100, where we intend to demonstrate our approach to space based observation and optical communications.

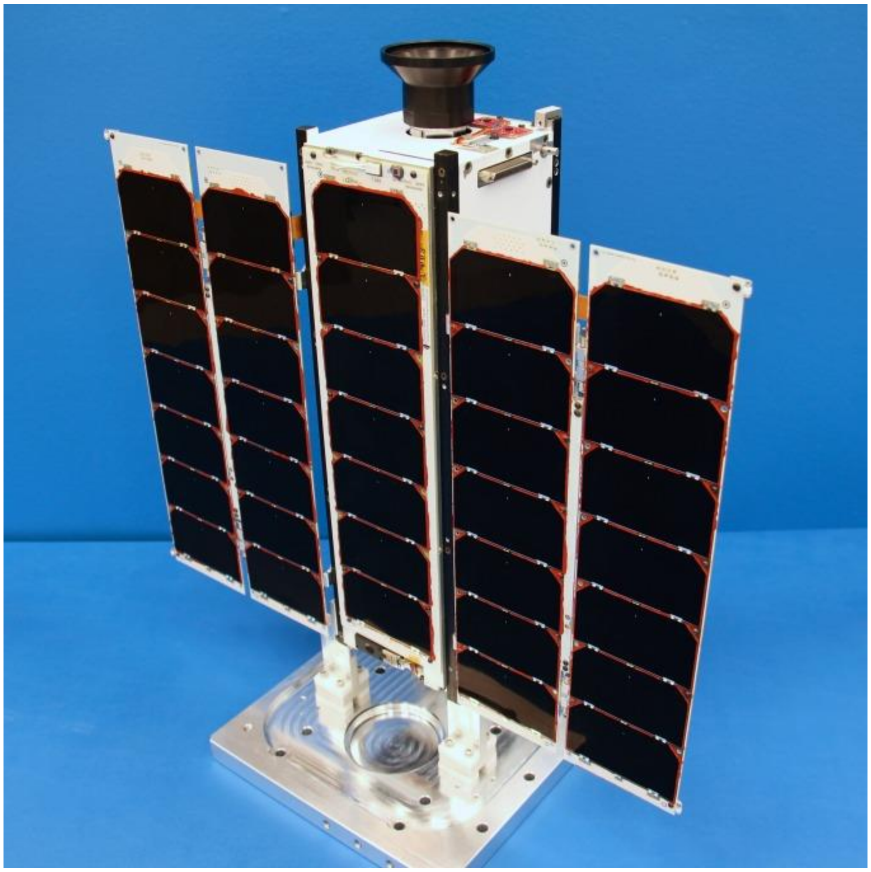


Figure 4-11, ARKYD 3 Test Vehicle [PRI]

Figure 4-12, An artist's concept shows Planetary Resources' Arkyd Interceptor spacecraft closing in on an asteroid. [nbcnews.com]

4.2.3 Shackleton Energy Company Roadmap:

Vision: The aim of this section is to provide a review of the architecture and business for the first commercial propellant depots to be deployed in space within a decade. The capability to refuel spacecraft in low Earth orbit (LEO) underpins a paradigm shift that considerably decreases cost and increases the mass of spacecraft hardware possible per launch because of the reduction of onboard propellant requirements. This same refueling capability also enables repeated long-duration high-thrust missions for commerce, exploration, and security to be carried out at superior price-performance, resulting from extensive reuse of in-space vehicles and systems. Shackleton Energy Company is establishing initial propellant depots in LEO using propellants launched from Earth to commence sales and deliveries within 5 years from program start, followed by deliveries of water-derived propellants from the lunar poles within an additional 5 years. By sourcing the propellant from the Moon's lower energy gravity well, significant reductions in operating costs are possible, with additional infrastructure costs amortized over multiple sales cycles. The most readily accessible and operationally robust source of cryogenic liquid oxygen and liquid hydrogen is from the craters situated at the poles of the Moon, in the original form of water ice.

Goals - Objectives:

Goal: Shackleton Energy Company (SEC) is embarking on an industrial program establishing propellant depots in space for commercial and governmental customers using fuel sourced from vast water ice deposits at the north and south poles of the Moon.

Expected Changes from Low-cost Propellant in space:

- Will change the way space launch providers operate today,
- Greatly reduce the cost to operate beyond low Earth orbit (LEO), and
- Will stimulate a new-age Gold Rush off of Earth not only for lunar ice but also for minerals and other resources that can be leveraged for financial and societal benefit.
- As gold opened the American West in the mid-19th century, and lunar ice will similarly open cislunar space by the early 2020s by fueling the space frontier.

Approach:

The establishment of lunar-sourced propellant depots represents a significant business opportunity that will be implemented with private investment to ensure that cost, schedule, performance, and risk are managed effectively, providing the fastest delivery to market. SEC's detailed and proprietary enterprise model conservatively forecasts hundreds of billions of dollars in revenues over a 20-year operational timescale, with initial revenues from federal and commercial customers occurring within 36 months of program start.

LEO Refueling: A spacecraft maneuvering from LEO to geostationary transfer orbit will consume 42% of its initial mass in LEO as propellant. For higher orbits, the propellant burden from LEO is even greater, as can be seen in Table 4-1. Therefore, the capability to refuel spacecraft in LEO underpins a paradigm shift that considerably increases the mass of useful spacecraft hardware possible per launch because of the reduction of onboard propellant requirements.

Lunar Sourced Water: The combined advantages of cryogenic propellant refueling capability sourced from lower energy and operationally accessible locations mean that access to lunar-sourced water becomes an essential requirement for expanding infrastructure off Earth. Building upon early sales from first-generation depots, SEC will harvest this readily available, abundant supply of natural resource as the feedstock for extensive propellant production by building the world's first full- scale refueling stations at strategic locations in LEO and beyond to provide significant cost savings to customers operating in space.

Business Case Summary: Our extensive analysis shows that the business case closes profitably within a decade, with first revenues generated 36 months from program start. Following break-even, additional integrated business streams enable exponential growth as a purely commercial venture. As such, SEC is now actively engaging investors and strategic partners to undertake initial risk reduction activities as milestones on the path to program implementation. In order to achieve first-to-market advantage, concurrent program planning and execution are essential, with the best talent and technology available worldwide.

Program Overview:

SEC’s team originates from exceptional engineering and expeditionary heritage and has laid the foundation for the establishment of an end-to-end supply chain for propellant provisioning (depots), supply (tankers and refineries), and source (lunar operations). The program is structured over four major risk reduction phases, each consisting of multiple success-driven milestones.

PHASE 1: PRELIMINARY DESIGN

This phase consists of detailed planning and design of all system elements, specific technology risk reduction, customer outreach and integration, regulatory coordination, and capital structuring. A highly detailed work breakdown structure has been constructed and team positions have been defined. The results from this 18-month foundation phase will be directly driven into the Phase 2 Prospecting and Phase 3 Infrastructure programs on concurrent fast tracks. SEC’s design philosophy is to build robust, resilient, and redundant modular components on an industrial production line, minimizing clean room fabrication where possible; extraction vehicles on the lunar surface or depots undertaking many cycles of refueling will experience operational burdens usually found in the oil exploration and mining sectors.

PHASE 2: ROBOTIC LUNAR PROSPECTING

To build upon the data already obtained by international lunar orbiting missions, SEC will build, test, launch, and operate several rovers that will continuously prospect for water ice and other volatiles and then generate in situ assay maps in selected lunar craters for the duration of the prospecting missions. SEC intends to launch multiple rovers to the lunar poles, employing production design principles of the main architecture, to provide maximum prospecting coverage, while system and subsystem redundancy will be utilized to ensure fail-safe operations (Fig. 4-13). Cooperation with NASA scientists and operators is being coordinated through a Space Act Agreement with all NASA centers. [note: the following figures come from their website]

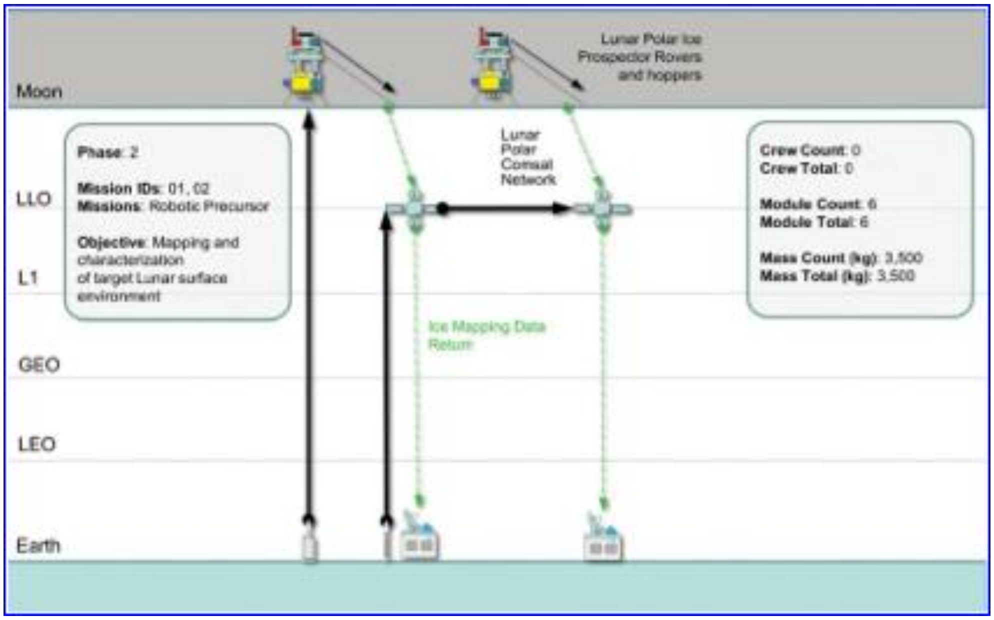


Fig. 4-13. Phase 2 Lunar Prospecting consisting of semi-autonomous rover missions for the identification of location and composition of highest yield ice deposits inside lunar craters.

PHASE 3: INFRASTRUCTURE DEVELOPMENT

In Phase 3 (Fig. 4-14), SEC will develop, test, and space-qualify mission-essential elements required in Phase 4 (Operations). These risk reduction elements include both in-space and lunar surface capabilities. Common system elements to be defined include power provisioning, lunar surface mining and processing equipment, in- space transport systems, life support systems with tele-assisted medicine, and a LEO space operations center with inflatable systems for a variety of applications. Inflatable systems include both manned and unmanned transport spacecraft, space/lunar habitats, work facilities, staging areas, and fuel storage.

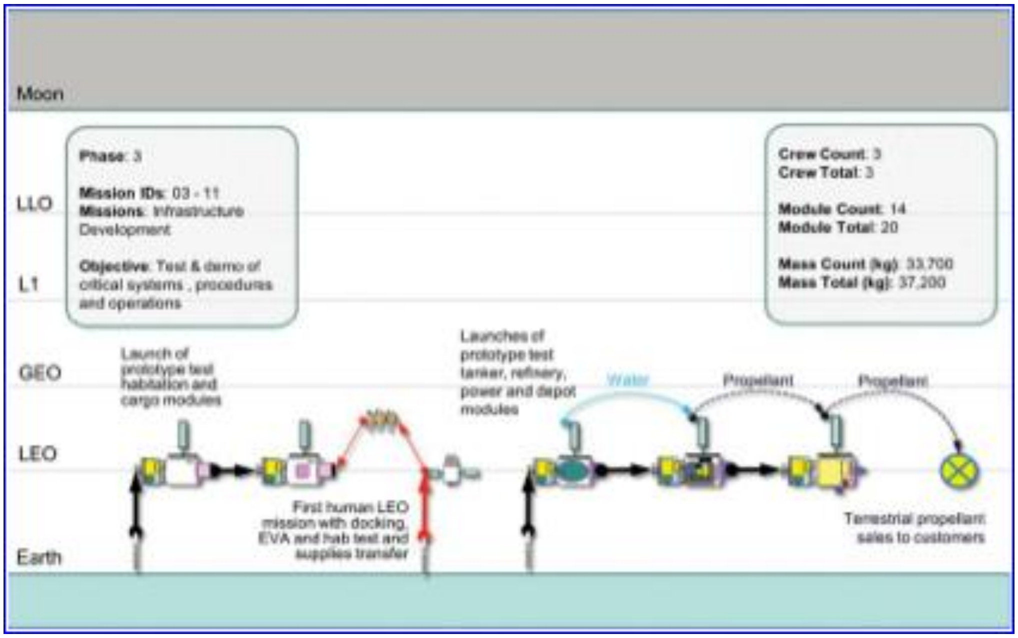


Fig. 4-14. Phase 3 Production line development of interchangeable spacecraft components will herald an industrial scale approach to space infrastructure.

To create customer awareness, build confidence, and meet their mission needs, subscale prototype depots will be inserted into LEO to provide early propellant deliveries within 5 years from program start. This introductory system will provide early revenue streams to offset capital expenses. SEC will initially provide liquid oxygen (LO_2) and liquid hydrogen (LH_2) to the LEO depot to start operations. Thereafter, water will be launched to LEO for conversion to LO_2 and LH_2 using prototype refining systems that will mature over time for industrial- scale production.

Building upon the presence of first-generation depots in LEO, a fleet of spacecraft will then be developed to establish the full supply chain of low-cost propellant provisioning. Transport of water from the lunar surface to LEO via low lunar orbit (LLO) with or without tank exchange at LLO will be undertaken by modular tankers supplying refining vehicles that will process water lique faction to constituent LO_2 and LH_2.

PHASE 4: PRODUCTION, MINING, AND OPERATIONS

Once developed to satisfactory levels of readiness (which will include orbital testing in all cases), each vehicle module will be incorporated as a baseline system in Phase 4. Extensive use of existing capability (e.g., lessons learned, technology, safety procedures, human operations, test infrastructure) from NASA will reduce programmatic risk and defray investment costs in Phases 3 and 4. The industrial architecture required for the establishment of a full propellant supply chain includes establishment of significant in-space and lunar surface components (Fig. 4-15).

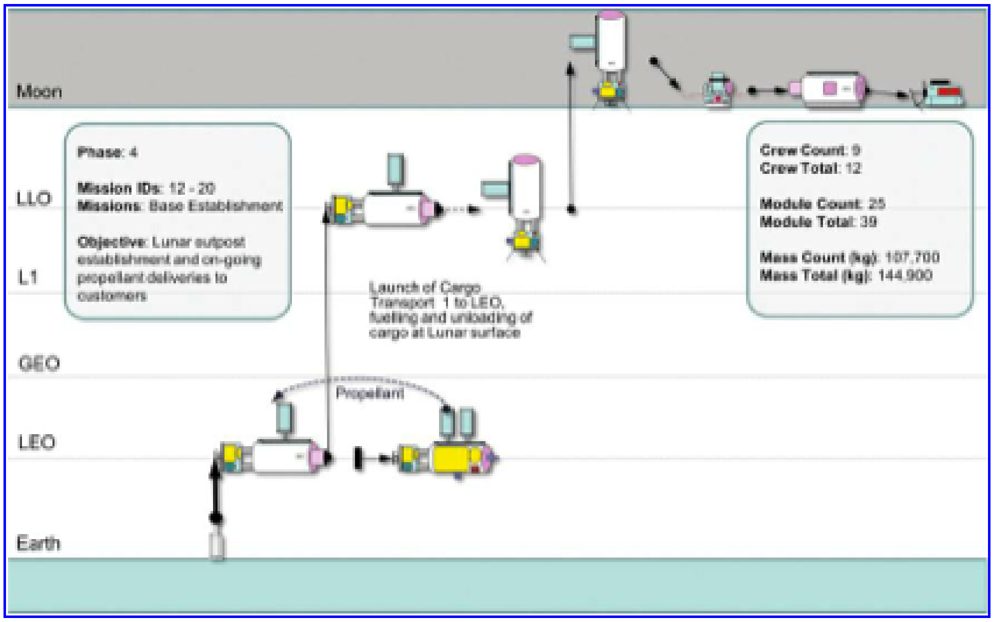


Fig. 4-15. Functional components of Phase 4 architecture will be deployed in space and on the lunar surface before industrial crew arrival.

Transportation and storage vehicles with common propulsion system units, inflatable cores, common power, and life support capabilities will be deployed ready for setup and utilization. As soon as the primary operational architecture has been deployed, SEC's crew will be deployed in space to the LEO Operations Center and the first lunar outpost at the selected lunar pole (Fig. 4-16). Undertaking remote critical testing and checkout further reduces program risk, enabling the crew to concentrate on operations once production is underway.

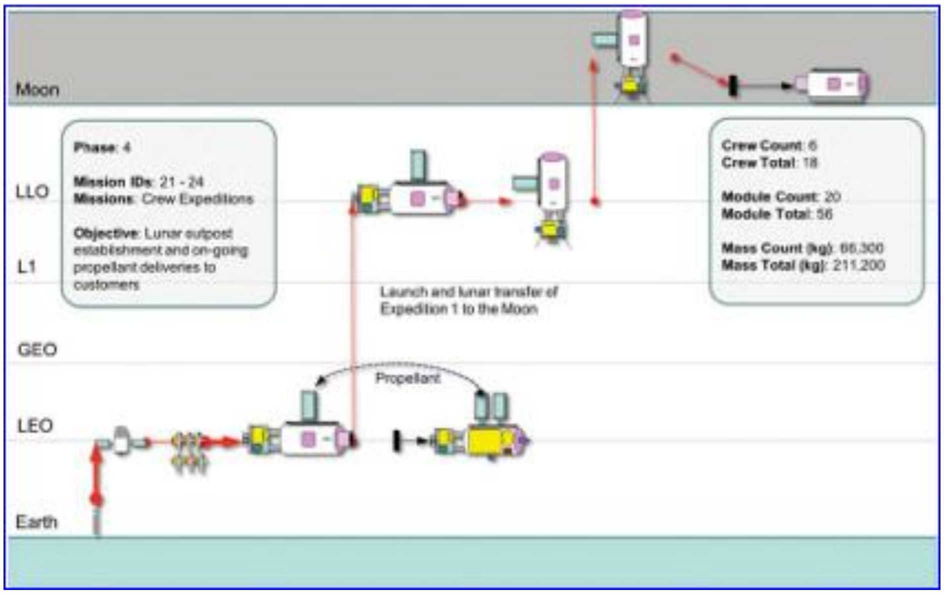


Fig. 4-16. Deployment of Shackleton Energy's industrial crew in space and on the lunar surface to begin and maintain production operations to schedule.

With production facilities in place at the lunar polar base, and the first propellant depots ready for operations, the full supply chain of water tankers between the lunar surface and orbital depots will commence (Fig. 4-17). Water extraction operations will occur based upon data received during Phase 2 of the program to ascertain the highest yields and composition of ice in the craters. Design of mining and processing facilities in Phase 3 will be undertaken by SEC's lunar mining operations in readiness for Phase 4 operations. Water-carrying tankers will return to LEO on a 90-day aerobraking cycle to conserve propellant. Once water has been transferred, the tankers return to LLO and the lunar surface. Every mission to and from the Moon to LEO will be optimized for provisioning, equipment transport, and other logistics support needs.

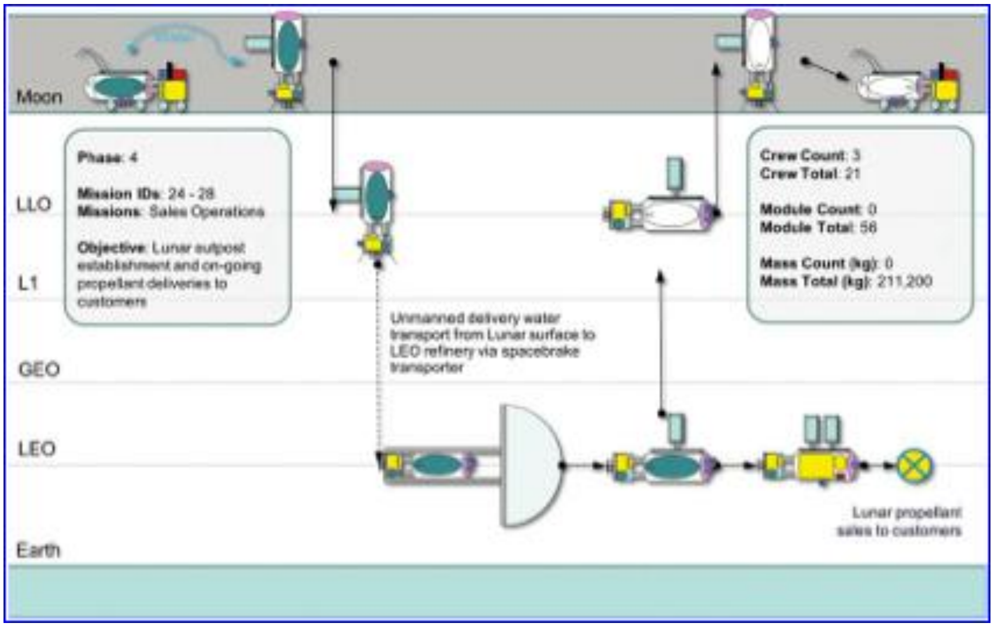


Fig. 4-17. Water tanker transportation supply chain and delivery to propellant depots.

Conclusions:

SEC has established a world-class team and consortium of strategic partners ready to open new space-based markets at high rates of growth and rapid investor return. By integrating multiple industrial services around a propellant depot architecture, with the bold leadership necessary to open a new frontier, SEC's proven team is establishing the platform for an entire space-based economy beginning operations and sales this decade. With exceptional net present values, the program provides a clear and robust investment proposition offering new market growth of the scale of the industrialization of the mid-1800s. The establishment of this fully commercial program will generate billions of dollars in profit, early return on investment, stimulate thousands of jobs, underpin national economic growth, and provide a resilient platform for addressing the significant challenges that will affect the populations of our planet throughout this century as we open up Earth's economic frontier for the benefit of all.

4.2.4 Excalibur Exploration Roadmap:

Goal - Excalibur's purpose is to conduct space exploration and resource development. Over the last ten years, Excalibur has conducted multiple studies under contract with major space faring corporations. The three that are of most relevance are:

1) “COSMOS” study looking at rendezvous with Toutatis asteroid
2) Excalibur Exploration Asteroid Rendezvous Mission by MDA of Canada
3) A Conceptual VASIMR Driven Asteroid Mission Architecture

All of these studies have shown that commercial ventures developing a SMR mining capability are viable and will greatly enhance the value of the investing company.

COSMOS Study:
This study, "Preliminary Examination of the Probe Flight to the Asteroid Toutatis,” was completed in May 2004 by Cosmos Ltd. It determined that a private prospecting mission to a near Earth asteroid was both technically possible and commercially feasible. Indeed, it seemed to be a bargain, if it could be accomplished for the prices estimated in this expert study. The conclusions from the first study are shown next.

- Excalibur Exploration’s commercial prospecting probe could be sent to the asteroid Toutatis.
- The flight time would be 1086 days beginning in early November 2008.
- The total cost was estimated to be $13-$23 million, including launch services.
- Maximum mass of 44.3 kg could be delivered to the asteroid if the launch date was November 2, 2008 (93 days counted from August 1, 2008).
- The landing unit "prospector probe" would be built using Russian technology.
- Launch services would be provided on a Russian launch vehicle from the Baikonur Cosmodrome in Kazakhstan.
- Preliminary trade studies considered the options of using launch services of the Soyuz, Dnyper and Rokot launch vehicles. 100 m/sec of maneuver capability was specified for the landing requirement due to the rotational characteristics of Toutatis.
- Total expenditures for the first flight (without account of expenses for ground operations and suppliers’ profit)
  --$ 15.7 M – optimistic variant with PAM-D
  --$ 23.8 M – pessimistic variant with PAM-D

--$ 13.8 M – optimistic variant with ARS
--$ 18.8 M – pessimistic variant with ARS

- The exploration payload "prospector probe" of the landing vehicle was designed on the basis of existing Russian hardware to meet the following mission requirements:

a) deployment of a radio beacon capable of transmitting a simple 100 bit message for at least 4 years;
b) exploration of the asteroid's materials' density;
c) characterization of the asteroid's materials' composition;
d) characterization of the asteroid's surface's particular features.

The image of the concept is as follows:

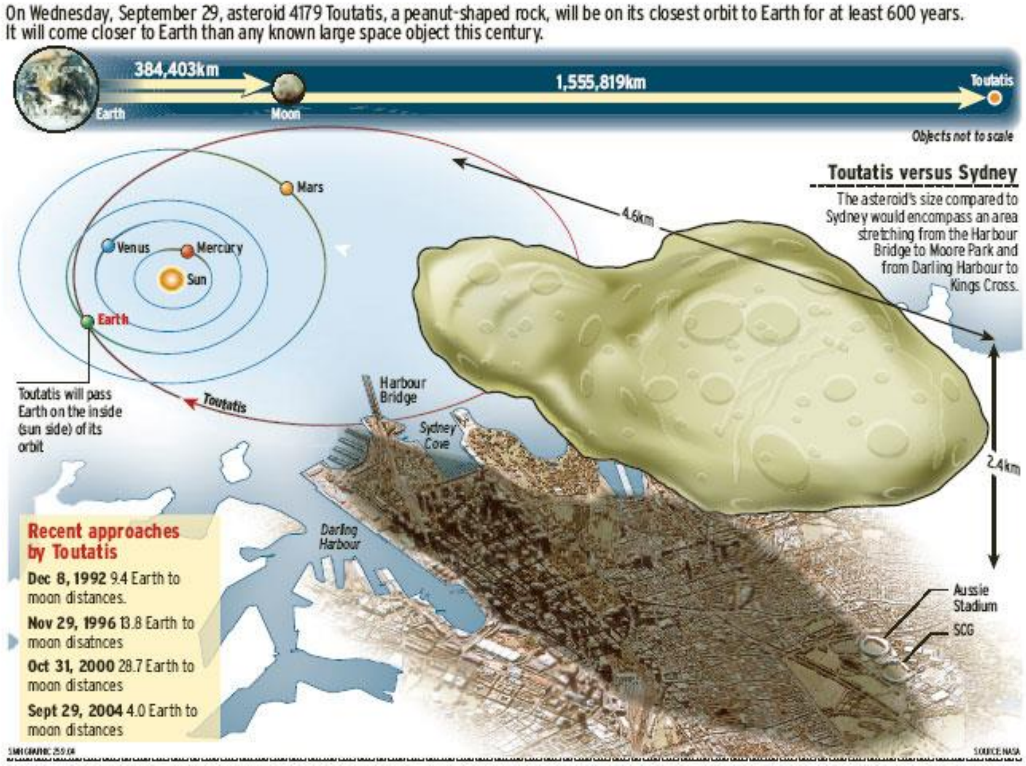


Figure 4-18, Toutatis Asteroid Opportunity [Excalibur Exploration]

Asteroid Demonstration Study: Beginning in 2005, Excalibur contracted with the firm MDA of Brampton, Ontario for studies including a Pre-Phase A Asteroid Demo Study (February 2006) and an Asteroid Rendezvous Mission Preliminary Foreseeability Study (November 2006.) The purpose of these studies was to provide independent technical verification and validation of the results in the Russian Cosmos Toutatis study; to compare Western study costs to Russian costs; and to compare the estimated mission costs. Another purpose of these studies was to provide more detailed technical, financial, concept of operations and mission planning in order to support launch license applications and the establishment of government and corporate partnerships. These two MDA studies were roughly equivalent to the Cosmos study; but, they were done in more technical detail. The MDA mission cost estimate was $100 to $150 million, roughly 5 to 8 times the cost estimate of the Cosmos study. The conclusions and recommendations of the MDA studies are:

Conclusions:

- Within a cost range of USD$80M – 100M, a "landing, surface sample & beacon" mission is the most practical and useful mission that will demonstrate some of the technologies required for follow-on commercial mining missions.
- Based upon preliminary trajectory, launch mass and payload mass analyses, 27 "mine-able" targets have been identified.
- Potential launch vehicles, spacecraft and ground stations that fulfill the demonstration mission requirements.
- The most appropriate option for ground station is to lease time on an existing deep space antenna/array.
- In terms of the Mission Control Complex (MCC), the most reasonable option is to retrofit existing company facilities into a mission control centre.

Excalibur Exploration
Asteroid Rendezvous Mission
Preliminary Mission Design Study

Prepared by:
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Brampton, Ontario
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MDA-R 0064

Prepared for:
Excalibur Exploration

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Figure 4-19, Asteroid Rendezvous Mission

Recommendations:

- Of the 27 candidates, asteroid Norwan is the most promising target and is recommended for in-depth trajectory, taxonomy, spin rate and

suitability analyses for the demonstration mission.
• From the list of potential targets and mission mass analyses, a list of recommended payload instruments for this mission were identified.
• An anchoring mechanism using harpoons with catches to secure the spacecraft to the surface of the target is recommended for further analysis.
• This report highly recommends the baseline system be considered for the demonstration mission. The baseline system is similar to the Russian Phobos-Grunt mission in 2009.

VASIMR Study: In August 2007, Excalibur contracted with the Ad Astra Rocket Company of Houston, Texas (AARC) for a study of the potential benefits of using AARC's variable specific impulse magnetoplasma rocket motor (VASIMR) instead of conventional chemical propulsion on the asteroid prospector mission. An attractive option of the proposed VASIMR spacecraft is that of a “seeding” mission, whereby the VASIMR® spacecraft is used to drop off several 100 kg radio transceiver beacons while at the same time analyzing mineral content during extended mapping orbits around several asteroids. This type of mission may be especially attractive to a prospecting mining company; and, it permit Excalibur Exploration and its investors to stake a claim of resource ownership on the target via beneficiation, thereby securing the rights for future mining activities for all asteroid bodies visited and studied by the VASIMR spacecraft. In a similar way, claims could be sold to other groups and organizations, thereby wholly or partially subsidizing the initial mission costs. The tracking and science details of these asteroids could also be sold to national governments for collision tracking –avoidance; and, to the world’s science organizations for in-situ analyses of asteroids and captured comets. If timed correctly, a 200 kW, 8000 kg VASIMR spacecraft is estimated to be able to deploy 100 kg instrument payloads with radio beacons to 4 individual asteroids with orbits similar to the Norwan asteroid. A VASIMR driven spacecraft that employs existing state-of-the-art solar cell technology with an alpha of 3 kg/kw is able to achieve significant mass and mission duration savings over chemical thruster technology. VASIMR missions should be able to achieve a built-in level of flexibility never before possible with previous thruster technology, enabling the possibility of large payload fractions to near Earth asteroids, small spacecraft (<6000 kg) sample returns, and rendezvous and mapping of multiple near Earth asteroids in a single mission. It was found that a 6000 kg VASIMR spacecraft in LEO could rendezvous with the Norwan asteroid and return to Earth with a 50 kg asteroid sample.

A Conceptual **VASIMR®** Driven Asteroid Mission Architecture

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Prepared for:
Excalibur Exploration

Figure 4-20, VASIMR Asteroid Mission [Excalibur Exploration]

The resulting roadmap for this commercial venture is composed of three phases. All are critical to the success of the venture with different levels of funding and risk. Each of the phases are described as:

Phase One: **Initiate the business on Earth**
2014-2020
Phase Two: **Execute a prototype flight to potential asteroids**
2015-2022
Phase Three: **Initiate mining operations with return of product**
2018-2029

Phase One: Initiate the Business on Earth [2014-2020]

This phase will emphasize SMR business preparation. It will include legal, managerial, technological, and international issues by:

- Excalibur will continue its program of educating the public and key decision-makers comprising political leaders, the investment community and national sovereign wealth funds.
- The International Academy space mineral resources cosmic study will be published and made broadly available in hard copy and as an e-book.
- A list of critical decision-makers will be compiled and direct marketing will be done to all of them.

Next, an aggressive program of development and protection of intellectual property will ensure that Excalibur has a position in the critical know-how that will be required for space mining. Ideally, Excalibur would like to sell shovels and groceries, and perhaps a little whiskey, instead of being a miner itself. Licensing intellectual property will be the biggest business of the future as we increasingly become an information society. It's certainly been a good model for General Electric, which is made billions licensing its patent portfolio. Of course, all the space mining companies know how important this is, so there will certainly be a rush to the patent office. Specifically, Excalibur believes that most of the critical technology used for space mining will be developed before the industry gets "off the ground." Historically, the patent on a steam engine, an airplane and intellectual property protection for computer programs has created some of the biggest industries, and the most profitable ones, of the last two centuries. We feel this is a good model to emulate. As to the exact technology, it's no secret that the cost of getting into space must eventually be reduced by several orders of magnitude. Long-term this means we must build many space elevators. Short term means that Excalibur must support lower access to space programs such as space elevators and commercial launch vehicles. But for a space miner, a critical technology will be how to move metal back to the Earth's surface so it can be delivered to the buyer. Excalibur has filed a patent application on a technology that can accomplish this.

Next, and in support of protection of intellectual property, Excalibur is working with major aerospace departments at universities around the world to develop new technology. The specific technology that needs to be developed is an adaptation of the Mond refining process for nickel to a micro gravity environment. There is also some synergy between asteroid mining, additive manufacturing and the use of in situ resources. As Excalibur shares the economic benefit of its patents with academic inventors and researchers, we have no shortage of willing brains. And, as the old saying goes, "the more brains, the more brainstorms."

Moving from the technical to the legal, Excalibur is working to obtain national licenses to conduct space testing of critical technologies. This part of the ground work should be completed by 2016. We are also keeping a weather eye on developments in national and international law that would affect the ownership and sale of space mineral resources.

Excalibur has identified, and is developing presentation material for, metal brokers with the goal of executing a future delivery contract for nickel and platinum group metals. This is the most important and sensitive part of the company's forward business planning.

Phase Two: Execute a Prototype Flight to Potential Asteroids [2015-2022]

There will be multiple steps in this phase. As a result, Phase Two has two in-orbit precursor missions. The first is the development of mining processes and equipment to be tested in low Earth orbit; and, the second is the VASIMR visit to multiple asteroids for testing of material proportions and identification of orbits and individual characteristics, such as spin rates.

The first orbiting test activity will be to develop and test the equipment in the low Earth orbit environment to ensure the design requirements have been met and the operations teams are ready. Once the technology has been developed to a laboratory bench scale, and the future position in the delivery of metal has been executed by credible buyer, Excalibur will be in a position to obtain financing for large-scale ground testing and in space proof of concept testing that will be required to buy down the risks of the business. This will take about two years and will cost in the low tens of millions of dollars. Excalibur is working with one of its sister companies to adapt two reusable reentry vehicles that have been flight tested for use as on orbit material science labs to support this orbital test program in 2016 to 2018. This space laboratory must be self-financing; and, it must make a profit. Excalibur is working with the International Space University and other organizations around the world on the space laboratory. The laboratory spacecraft will not be dedicated to space mining. It will be available for use by anyone to do science or equipment qualification in space. Specifically, it will be available to other space mining companies on a nondiscriminatory basis. Virtually all of the robotic technology needed for our Excalibur's space Mond facility can be tested on the ground. However, it will have to be flight tested to ensure that we have eliminated all of the failure modes. This is not a government space program. If we fail, we will probably be out of business.

The second on-orbit test project would be the proposed VASIMR spacecraft as a "seeding" mission. This mission would drop off several 100 kg radio transceiver beacons, while at the same time, analyzing mineral content during extended mapping orbits around several asteroids. This type of mission may be especially attractive to a mining prospecting company, and would permit Excalibur Exploration and its investors to stake a claim of ownership of the target resources via beneficiation, thereby securing the rights for future mining activities for all asteroid bodies visited and studied by the VASIMR spacecraft. A final trade study found that an 8000 kg VASIMR spacecraft could visit 4 near Earth asteroids in a "seeding" mission mode, dropping off 100 kg radio beacons on all 4 asteroids. The VASIMR spacecraft is also able to be reused once a primary sample return mission is complete, giving the end user the ability to achieve secondary mission goals or complete entirely new missions once refueled.

Phase Three: Initiate Mining Operations with Return of Product [2018-2029]

Once the space testing has been completed, we hope that a pilot plant can be launched on a single launch vehicle into low earth orbit. It would then be moved by low thrust electric propulsion along low-energy trajectories to a suitable asteroid, which we believe may be virtually any asteroid, where it will begin to refine metal and send it back to the earth in very small quantities. Once the methods of delivering the goods have been tested on small items, the money will be raised to send out a much larger facility with the goal of delivering about 10% of the worlds nickel to the earth from outer space. Once the cash flow has been established from this, the company will grow into an ordinary mining company. Platinum group metals are the other low hanging fruit, although they are much more difficult to extract than nickel. They are, however, correspondingly easier to return to the earth.

In parallel with the development of the large-scale production of these valuable metals and their delivery to the earth, specialized mining equipment will begin recovering water and other raw materials that have value in space. To the degree that is feasible, these materials will be beneficiated in space. For example, the water might be converted into hydrogen and oxygen. The carbon might be made into organic materials. It's not out of the question that we might even grow food. Fortunately for Excalibur, almost any asteroid selected at random contains a great deal of valuable material; so, our selection process will be driven by cost. In space, this cost is derived by the energy to move, and the time to move, to and from the mining site.

In summary, the Excalibur Exploration Roadmap looks similar during the last two phases as they are based upon traditional space hardware development, testing and operations. Of course, as they are commercially driven SMR space ventures, the timeline will be condensed. Phase one will be expedited as initial funding is critical; and, legal/policy issues must be resolved.

Table 4-2, Phase Two: Execute a Prototype Flight to Potential Asteroids:

Preliminary Mission Design Study	**01/04/15**	**07/30/15**	**145d**
Requirements Definition Phase	**07/31/15**	**10/10/15**	**50d**
Develop Customer Requirements	07/31/15	08/27/15	20d
Develop Operation Concept	08/14/15	09/25/15	30d
Operations Concept Review	09/25/15	09/25/15	0d
Develop System Requirements	09/12/15	10/10/15	20d
System Requirements Review	10/10/15	10/10/15	0d
Develop Program Plan	07/31/15	09/25/15	40d
Design	**10/10/15**	**05/08/17**	**390d**
Preliminary Design	10/10/15	04/22/16	130d
Ground Control Segment	10/11/15	11/07/15	20d
Ground Scientific Complex	11/08/15	02/11/16	60d
Launch Complex	02/12/16	03/10/16	20d
Technical Complex	03/11/16	04/08/16	20d
Launch Vehicles	10/10/15	04/22/15	130d
Launcher	10/10/15	10/10/15	0d
Space Head Module (Bus & Payload)	10/11/15	04/22/16	130d
Detailed Design	04/23/16	05/08/17	260d
Ground Control Segment	04/23/16	06/18/16	40d
Ground Scientific Complex	06/19/16	12/22/16	130d
Launch Complex	04/23/16	07/17/16	60d
Technical Complex	07/18/16	10/10/16	60d
Launch Vehicles	10/14/16	01/15/17	60d
Launcher	04/23/16	05/08/17	260d
Space Head Module (Bus & Payload)	04/23/16	05/08/17	260d
Engineering Model MAI&T	04/22/16	04/22/16	0d
Manufacturing	**11/04/16**	**11/03/17**	**248d**
Flight System Assembly & Integration	**07/13/17**	**04/26/18**	**197d**
System Testing (Verification)	**03/30/18**	**09/27/18**	**130d**
Launch - Low Earth Orbit Test Facilities	**09/27/18**	**09/27/18**	**0d**
Launch - VASIMR	**09/27/18**	**09/27/18**	**0d**
On-Orbit testing of manufacturing facilities	**10/18/18**	**06/24/20**	**540d**
Cruise jfor VASIMR Mission	**10/18/18**	**06/24/19**	**180d**
Rendezvous and Mission Operations	**06/27/19**	**06/22/22**	**980d**

Table 4-2, Phase Three: Initiate Mining Operations with Return of Product

Preliminary Mission Design Study	**01/04/18**	**07/30/18**	**145d**
Requirements Definition Phase	**07/31/18**	**10/10/18**	**50d**
Develop Customer Requirements	07/31/18	08/27/18	20d
Develop Operation Concept	08/14/18	09/25/18	30d
Operations Concept Review	09/25/18	09/25/18	0d
Develop System Requirements	09/12/18	10/10/18	20d
System Requirements Review	10/10/18	10/10/18	0d
Develop Program Plan	07/31/18	09/25/18	40d
Design	**10/10/18**	**05/08/20**	**390d**
Preliminary Design	10/10/18	04/22/19	130d
Ground Control Segment	10/11/18	11/07/18	20d
Ground Scientific Complex	11/08/18	02/11/19	60d
Launch Complex	02/12/19	03/10/19	20d
Technical Complex	03/11/19	04/08/19	20d
Launch Vehicles	10/10/18	04/22/18	130d
Launcher	10/10/18	10/10/18	0d
Space Head Module (Bus & Payload)	10/11/18	04/22/19	130d
Detailed Design	04/23/19	05/08/20	260d
Ground Control Segment	04/23/19	06/18/19	40d
Ground Scientific Complex	06/19/19	12/22/19	130d
Launch Complex	04/23/19	07/17/19	60d
Technical Complex	07/18/19	10/10/19	60d
Launch Vehicles	10/14/19	01/15/20	60d
Launcher	04/23/19	05/08/20	260d
Space Head Module (Bus & Payload)	04/23/19	05/08/20	260d
Engineering Model MAI&T	04/22/19	04/22/19	0d
Manufacturing	**11/04/19**	**11/03/20**	**248d**
Flight System Assembly & Integration	**07/13/20**	**04/26/21**	**197d**
System Testing (Verification)	**03/30/21**	**09/27/21**	**130d**
Launch	**09/27/21**	**09/27/21**	**0d**
Cruise	**10/18/21**	**06/24/22**	**180d**
Rendezvous and Mission Operations	**06/27/22**	**06/22/23**	**260d**
Mining Operations	**06/27/23**	**06/22/28**	**1830d**
Return of Minerals to Earth Region	**06/27/24**	**06/22/29**	**1830d**

Excalibur Exploration Summary: In 2008, Excalibur conducted a morphological analysis on how to develop a space mining business using the results of the studies above and its knowledge of technical, legal, economic and policy constraints. [Morphological Analysis is a method developed by Fritz Zvicky for exploring all the possible solutions to a multidimensional, non-quantified complex problem.] As a result of this morphological analysis, Excalibur drew 10 conclusions to guide its future actions:

1. The first material obtained from space should be delivered to a buyer on the surface of the Earth. It should be nickel metal at up to 10% of the annual world production, or about 16,000 tons/month.
2. The nickel chould be sold by Excalibur to a buyer using a contract for future delivery, thus establishing a "forward market" value for the business. It can then be discounted for net present value and risk to allow easier capital formation to finance the business start up. This is entirely a marketing, business, legal and economic activity. It eliminates risk of sale. These futures contracts can be structured so there is no risk to the buyer.
3. Platinum group metals (PGM) could also be sold for future delivery to a buyer on Earth, if this is technically and economically feasible, because of the high value to mass of these materials. This will require research and development.
4. Water, oxygen and other useful minerals such as bulk matter for radiation shielding, should be mined for storage in fuel and supply depots in space, initially at the Earth-Moon EML-1 or EML-2 points. These resources, which are required for living and working in space, will not have to be lifted from the 10km/sec gravity well of the Earth. These materials should be processed in space to add value whenever possible by mechanical or chemical processing; e.g. additive manufacturing. This area of research should be monitored and encouraged.
5. The Mond process for refining nickel should be adapted to the production of nickel in-situ at the asteroid mine site. Work on this should begin immediately and is critical.
6. Patent applications should be filed ASAP on inventions to: 1. refine the nickel in-situ at the mine site. 2. return the metal near to the Earth safely. 3. "Live off the land" by using in-situ materials from the asteroid mine site. 4. Land the metal on Earth

safely. 5. Launch the mining systems to the asteroid.
Each of these areas requires a profound conceptual shift that will result from key inventions. Development of a strong intellectual property portfolio must be a priority for Excalibur.

7. Materials from the Moon may be used to lower overall start up costs.

8. Legal and policy issues will be critical; and, then should be address in an internationally credible manner as soon as possible with the goal of allowing free markets and free commercial use of resources in space.

9. Forward contracts must be executed with credible metal brokers or buyers as soon as possible.

10. It is very, very important to remember that technical matters are not the most critical issues.

4.3 Comparison and Summary:

The future of SMR, as shown inside four competing company roadmaps, boils down to:

Phase One:	Initiate the business on Earth 2014-2020
Phase Two:	Execute a prototype flight to potential asteroids 2015-2022
Phase Three:	Initiate mining operations with return of product 2018-2029

Chapter Five, Quick Look at SMR Systems

This chapter will discuss systems concepts for SMR transportation and extraction technologies. It will be an attempt to organize these concepts into categories based on end uses, type or class of resource, and technology. It will briefly review the status of technological readiness and risk after discussions of the different technologies. The basic chapter breakout will be by Parts:

Part A – Systems Concepts are transportation & mining Production
Part B – Assessment technologies of readiness, utilization, and identification of risks.
Part C – Illustration of the Concepts by explaining current - future Design Reference Missions (DRM)

Part A – Systems Concepts are Transportation & Mining Production

5.1 SMR SUPPORTING SYSTEMS – Reusable Rockets

Supporting systems for SMR should be based upon a reusable paradigm that embraces repair and maintenance rather than expendability. For example, terrestrial mining equipment uses replaceable parts on a daily basis; and, to expect to be able to design SMR systems for long duration missions without a stock of replacement parts would be to design for failure. The expendable paradigm of space flight is seriously flawed. Discarding capital equipment after one use is an easy way to run costs upward to infinity, while constraining expectations regarding accessibility to the space frontier. The flawed logic of wasting infrastructure is intimately tied to the expendable rocket paradigm, where booster stages are designed to progressively separate from the payload that is trying to reach orbit.

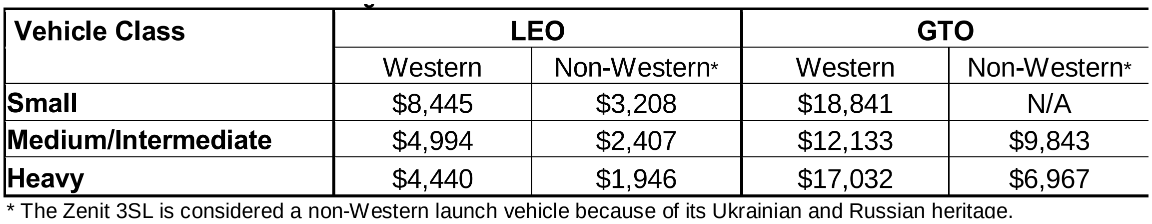
In addition to the concept of maintenance and re-use, future SMR architectures should be structured around future infrastructures. Two good examples for this would be the previously described space elevators and a cycler between Earth and Mars. This last one is a concept by Dr. Buzz Aldrin for a spaceliner continuously navigating between Earth and Mars in a solar orbit. Quick trips, by small shuttlecraft, would occur up/down from the planets, thus enabling a permanent infrastructure with easy resupply. This cycler concept is also valid between Earth and the Asteroid Belt.

Design for space transportation system reuse, as well as maintenance, will sharply reduce systems reliability requirements and, therefore, costs. This process rewards modular systems architecture (plug and play components such as batteries and sensor platforms which could be transferred to other units) and opens the door to mass production, standards, and interoperability. The enabling technological change will be access to resources at space depots. The ability to have water, fuel and air at locations of choice, at reasonable prices, will ensure that designs for transportation infrastructures will include equipment for the long run. The obvious example of this is a space tug that moves satellites around the GEO arc and refuels them at the same time. This could occur when GEO satellites are designed for those services and a space tug is positioned in the GEO orbit. The supply of water, fuel and air to the GEO space depot will enable this new paradigm to take hold and expand beyond Earth's orbits.

5.1.1 Earth and Orbital Transportation

Currently, the space booster business is undergoing changes. The ability to launch people to orbit has moved from the dominant position of US-Russia to a paradigm that includes Chinese and commercial transportation infrastructures. In addition, Europeans have added Soyuz capabilities to those Arianespace facilities in French Guiana, while the Indians and Japanese are planning for future capabilities for launching humans to space. Flexibility is one of the watch-words for new ventures with lower prices and more redundancy occurring. A side note, that could become significant, is the existence of a commercial venture to put people into space, not orbit, at a fraction of a million dollars. The next three charts show some numbers relevant to the discussion.

The next few pages compare the prices and approaches for commercial launches. There are two cautions: 1 – Prices vary greatly with time and capability to orbit, 2 – the first chart was accomplished in 2002; therefore the value of the dollar is different. [the inflation factor used is a 33% increase from 2002 to 2014 dollars]. The first chart summarizes the variability of numbers and the cost per pound to LEO and GEO [to estimate cost per kilogram, multiple by 2.2]. As time is passing, there is an improvement in pricing per pound to orbit from larger launch vehicles, in development of truly commercial ventures, and the expansion of the commercial satellite market.



Vehicle Class	**LEO**		**GTO**	
	Western	Non-Western*	Western	Non-Western*
Small	$8,445	$3,208	$18,841	N/A
Medium/Intermediate	$4,994	$2,407	$12,133	$9,843
Heavy	$4,440	$1,946	$17,032	$6,967

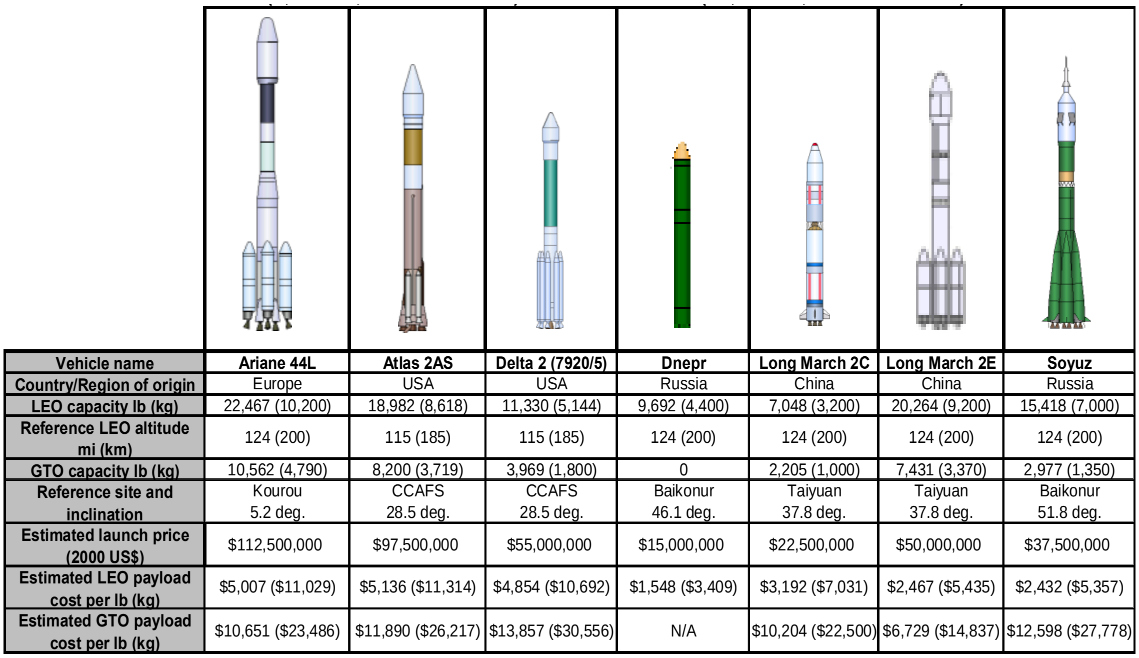
* The Zenit 3SL is considered a non-Western launch vehicle because of its Ukrainian and Russian heritage.

Table 5-1, Price per Pound to Orbit Comparison [Futron 2002].

Vehicle Class	LEO		GEO	
	Western	Non-Western	Western	Non-Western
Small	$ 11,200	$ 4,300	$ 25,000	N/A
Medium	$ 6,700	$ 3,200	$ 16,000	$ 13,000
Heavy	$ 5,900	$ 2,600	$ 22,600	$ 12,850

Figure 5-2, Price per Pound to Orbit Comparison. [2014 estimated by 1.33 inflation factor]

Another look at prices for launch vehicles [again in 2002] showed the variation in prices to LEO and to GEO. [Futron] The caution is that the Geosynchronous Transfer Orbit does not get the satellite to GEO and requires additional thrusting. The price increases for that is additional hardware and fuel. The next figure shows a variety of launch vehicles, with data from 2002.



Vehicle name	Ariane 44L	Atlas 2AS	Delta 2 (7920/5)	Dnepr	Long March 2C	Long March 2E	Soyuz
Country/Region of origin	Europe	USA	USA	Russia	China	China	Russia
LEO capacity lb (kg)	22,467 (10,200)	18,982 (8,618)	11,330 (5,144)	9,692 (4,400)	7,048 (3,200)	20,264 (9,200)	15,418 (7,000)
Reference LEO altitude mi (km)	124 (200)	115 (185)	115 (185)	124 (200)	124 (200)	124 (200)	124 (200)
GTO capacity lb (kg)	10,562 (4,790)	8,200 (3,719)	3,969 (1,800)	0	2,205 (1,000)	7,431 (3,370)	2,977 (1,350)
Reference site and inclination	Kourou 5.2 deg.	CCAFS 28.5 deg.	CCAFS 28.5 deg.	Baikonur 46.1 deg.	Taiyuan 37.8 deg.	Taiyuan 37.8 deg.	Baikonur 51.8 deg.
Estimated launch price (2000 US$)	$112,500,000	$97,500,000	$55,000,000	$15,000,000	$22,500,000	$50,000,000	$37,500,000
Estimated LEO payload cost per lb (kg)	$5,007 ($11,029)	$5,136 ($11,314)	$4,854 ($10,692)	$1,548 ($3,409)	$3,192 ($7,031)	$2,467 ($5,435)	$2,432 ($5,357)
Estimated GTO payload cost per lb (kg)	$10,651 ($23,486)	$11,890 ($26,217)	$13,857 ($30,556)	N/A	$10,204 ($22,500)	$6,729 ($14,837)	$12,598 ($27,778)

Figure 5-1, Comparison of prices for launch vehicles [Futron, 2002]

Now, for clarity, the following chart shows an update to the recent contracts by NASA, and other US launches. This chart is shown for price per kilogram to LEO, in 2012 dollars. This one shows roughly $10,000 per kilogram to Low Earth Orbit as the payload increases in mass. The one “outlier” in the data is the Falcon Heavy contract that is offering tremendous savings in launch price. SpaceX is the first approach at truly commercial pricing of launch vehicles. SpaceX has been very successful up to the start of 2015 and will influence the price to orbit for the next several years. Prices are coming down!

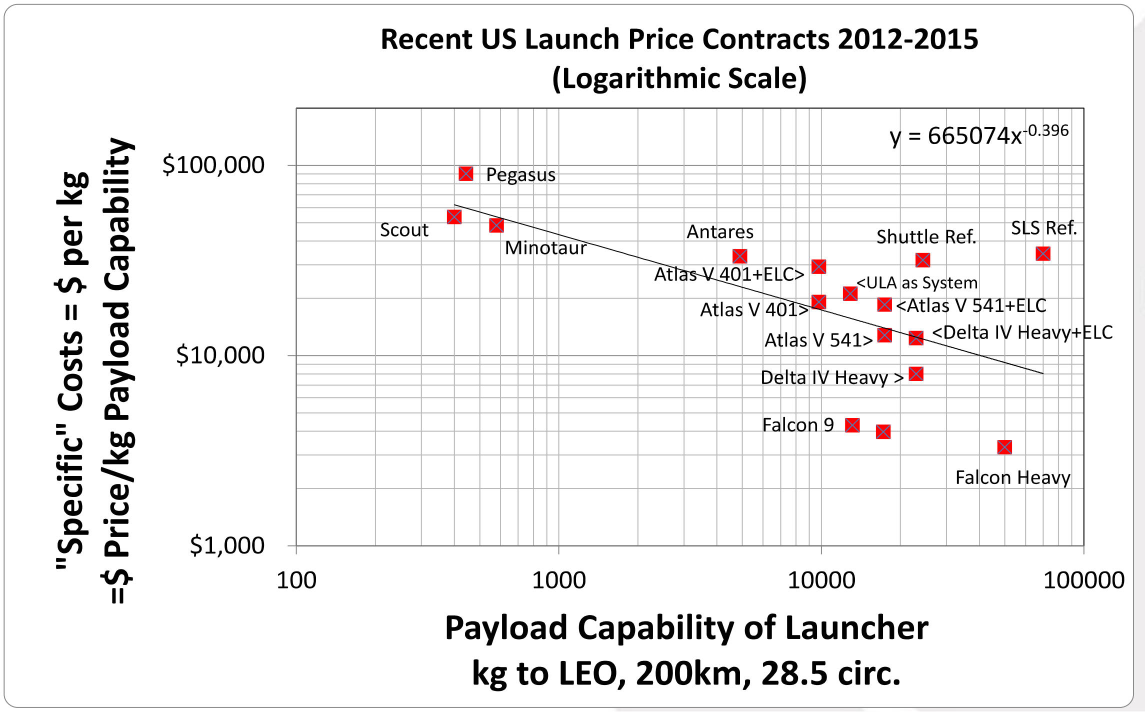


Figure 5-2, US Launch Price Contracts (2012-2015) LEO [Zapata, 2014]

To summarize the situation, space.stackexchange.com extrapolated some numbers to answer the question: How much does it take to get to GEO, when you know the price to LEO? This is very complex with many and significant variables. For clarity, the authors have summarized what was said so that the range of numbers can be used when calculating future space activities. The website projected the following:

Price to Geosynchronous Transfer Orbit [Stack Exchange]

Atlas V 401	$27,777
Delta IV Heavy	$25,424
Ariane 5 ECA	$24,079
Ariane 5 ES	$30,249
Proton-M	$16,620
Average	$ 25,000 per kg

In addition, the website extrapolated the cost to get from GTO to the cost to get to Geosynchronous Earth Orbit as twice the average:
$50,000 per kilogram.

If one were to take the numbers from SpaceX's website for estimates of launch prices in the future, the following falls out:

	Locations	Mass [kilograms]	Price	Cost $ per Kilogram
Falcon 9	To Geosynchronous Transfer Orbit [GTO]	4,850	$ 61 million	12,577
Falcon 9	To Geosynchronous Orbit [GEO]			25,000
Falcon 9 Heavy	To Geosynchronous Transfer Orbit [GTO]	21,200	$ 81 million	3,820
Falcon 9 Heavy	To Geosynchronous Orbit [GEO]			7,640

Table 5-3, Falcon 9 [+ Heavy] Prices per kilogram [SpaceX]

There would be tremendous savings if these numbers are achievable in the competitive commercial world. Even at $ 10,000 per kilogram, the price to GEO would be significantly better than currently available.

The expendable Earth-to-Orbit (ETO) approach achieved the Moon for the United States; however, cost was very high due to risk and complexity. There may be a better near term approach – one that demonstrates an on-orbit critical SMR capability – refueling from a terrestrially-supplied propellant depot. Heavy lift launch can increase satellite mass by refueling. [Kutter, 2009] and others show a significant performance increase with on-orbit operations and refueling. When one uses a depot for fuel [lifted against the gravity well at great cost], one does not save money on fuel; but, it increases the capability of the mission. Mission satellites can leverage the full capability of lift through the gravity well and refuel its empty tanks in orbit. This then allows them to climb to mission trajectory with more mission payload. However, it still takes two launches. To "beat" this concept, fuel could be supplied from an asteroid or from lunar surface operations.

In addition to the savings and performance promised by refueling, other strategies are possible for reducing the high cost of space launch. There is a belief that lowering launch costs will increase flight rates. Demand curves that are normal and elastic behave this way; and, there is no reason to doubt that added capacity and lower cost will have an accelerating effect on space settlement. Elon Musk's vision is to offer rides to Mars costing a passenger only $500k with his rocket company SpaceX [Eddy, 2012]. The strategy is based upon first implementing a reusable first stage, then extending reusability to upper stages. The schedule for implementing reusability seems to be on track, with no major roadblocks identified to date. However, enabling heavier payloads or lowering costs solves only part of the problem. One of the fundamental constraints of space launch is payload faring size, not just launch mass. This is due to the aerodynamic loading constraints of launch. The size (diameter) limit of space launch is harshly enforced by nature. A solution to this, in addition to on-orbit assembly, is in-space manufacturing. Note that the ISS was not able to launch in its current configuration using a single vehicle.

The goal is to lower cost of launch to a reasonable level. There are many commercial companies trying to achieve this goal. Let us hope this does decrease the cost to lift product through our gravity well. All will benefit from Elon Musk attaining some of his "reach-out" goals. As the current price to orbit is exorbitant, the need for SMRs is significant. The more that can be produced on an asteroid [or lunar surface], the more viable the movement into space becomes. Lifting off from planet Earth is still the dominant hurdle to be conquered.

Delta-Velocity (Delta-V) Assumptions

The most important variable influencing future propellant use is the energy 'cost' of space access, typically reported as change in velocity (or 'delta-V' in the aerospace industry). Because the SMR Strawman model estimates per-capita water consumption for space settlers, and because electrolyzed water is the most efficient chemical propellant currently known, these delta-Vs are a critical parameter in the modeling effort. For flight around our solar system, energy propulsion must be estimated. This is accomplished with the term “delta V” with the recognition that the largest current demand is Earth to LEO lift against the gravity well. As such, the stated need is somewhere around 9.5 km/s of velocity added to the vehicle to be in orbit. Above LEO, the needs are mostly in the one to three kms/sec for long distance travel. Of course, these are the lowest energy trajectories and time to delivery can be improved by expending more fuel.

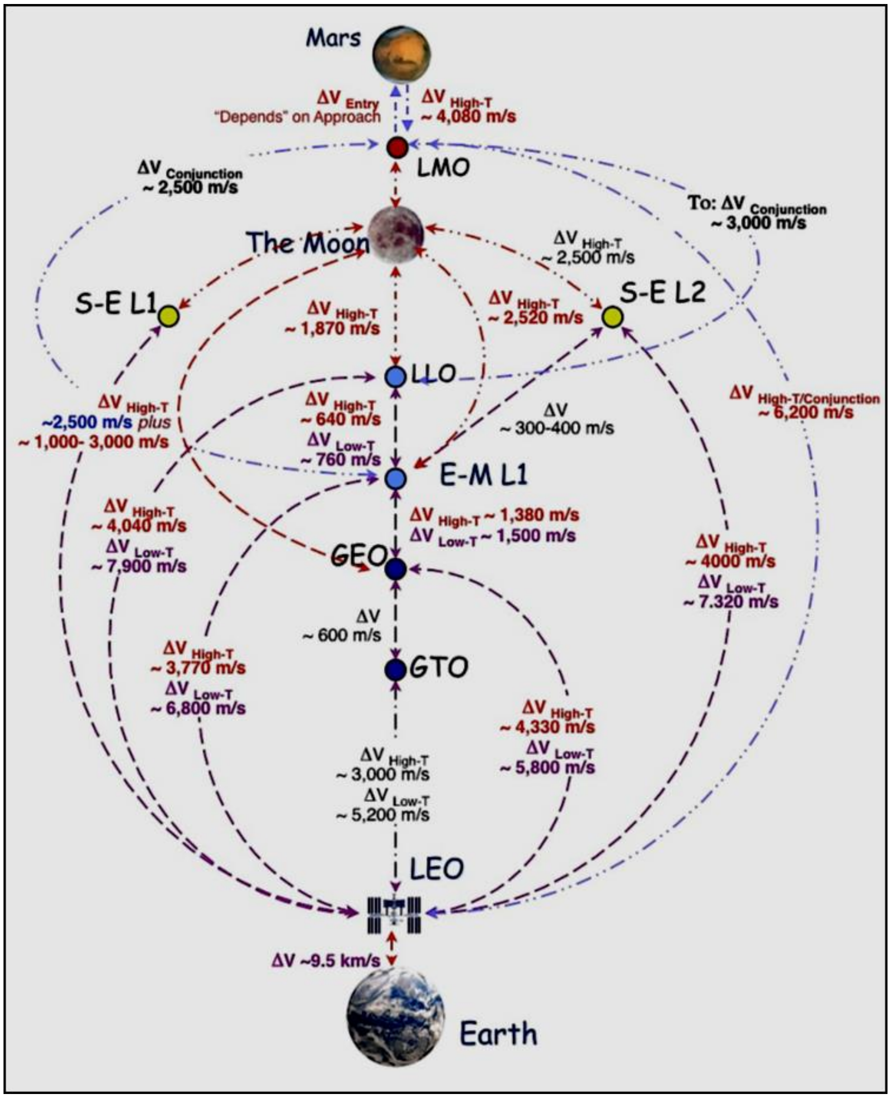


Figure 5-3, Delta-Vs in Earth’s Neighborhood [Mankins, 2011].

5.1.2 In-Space Transportation

In-space transportation is a challenge that is being addressed by many. The next few images show some of these plans. The concept of coasting to Mars for 8.5 months is the standard for NASA missions. The astronaut Franklin Chang Diaz is designing [and testing in space soon] a new concept of propulsion inside a vacuum. His Variable Specific Impulse Magnetoplasma **Rocket** [VASIMR] motor enables rapid transit to solar system destinations. With his motor, visits to asteroids could become routine. Movement of product from mining facilities around the solar system would occur within a financial package making refueling depots wise investments. Of course, this is only one man's vision and there are many others that see in-space transportation as a real possibility once the fueling and depot concepts are validated. Refueling a reusable transportation motor at GEO or EML-1 will ensure movement throughout the solar system at reasonable prices.

Figure 5-4, of VAISAMIR High Efficient Rocket [AdAstra]

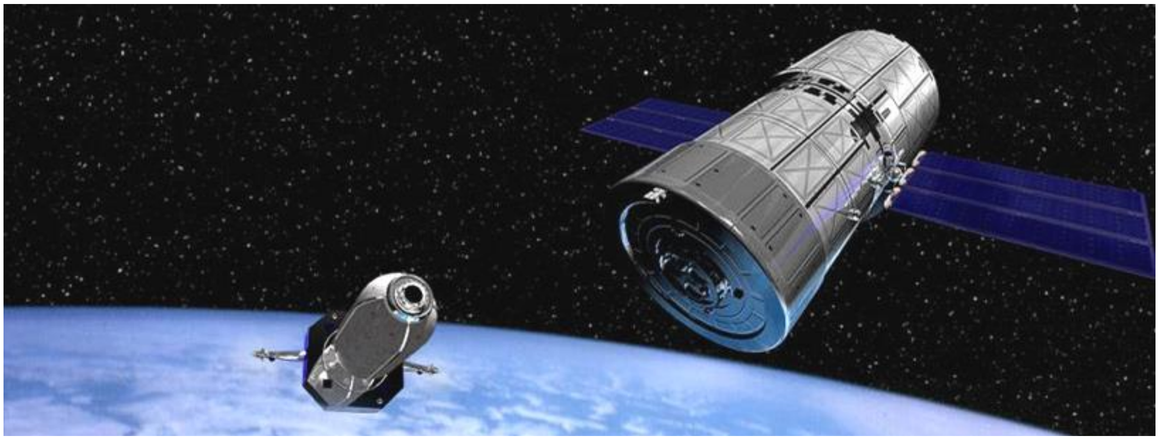


Figure 5-5, Crew Transfer Vehicle –
Hybrid Propellant Module [Troutman, 2001].

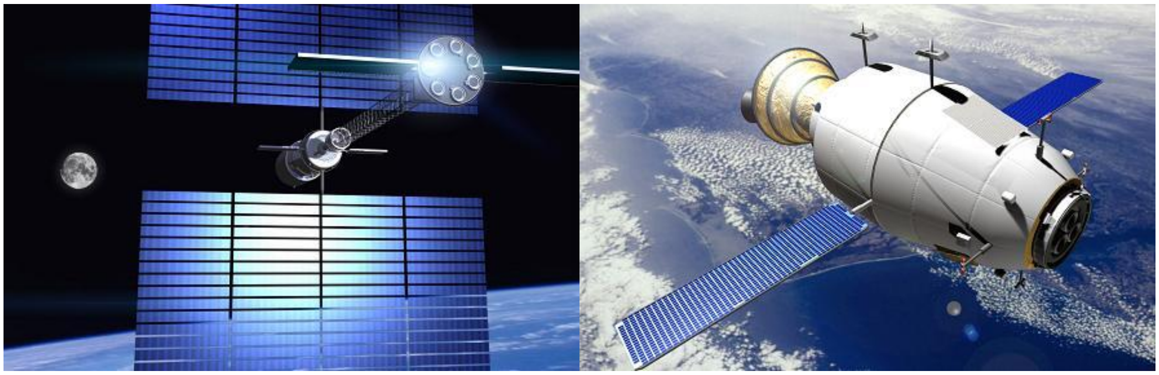


Figure 5-6, Solar Electric Propulsion and
Chemical Transfer Vehicles [Troutman, 2002].

Another approach to transportation capability for Moon-Mars space access is within easy reach should currently expendable systems begin to be refueled and reused. A relevant example is the Centaur upper stage which is currently used a single time before it is parked or discarded. Over 100 Centaurs remain in orbit, waiting for a propellant source. Extensive published work of Zeigler & Kutter map the technology demonstration paths to a fully reusable Centaur [Kutter, 2010]. United Launch Alliance (ULA) propose a future common upper stage:

> *"Currently in preliminary development, the Advanced Common Evolved Stage (ACES) and human rating will substantially enhance ULA's ability to support its customer needs. With conceptual development of partial booster reuse, orbital refueling, long-duration stages, and long-duration cryogenic propulsion stages,*

> *ULA is setting the stage to provide revolutionary space transportation in the years ahead."* [Kutter, 2010].

The reuse of upper stages could extend the reach of many of today's international launch vehicles. In fact, models showing reuse of upper stages typically encounter a very big problem: identification of customers to use the excess capacity. Space settlement and the creative vision of entrepreneurs offer an easy solution to this problem.

Transportation of Ore to Processing Facilities

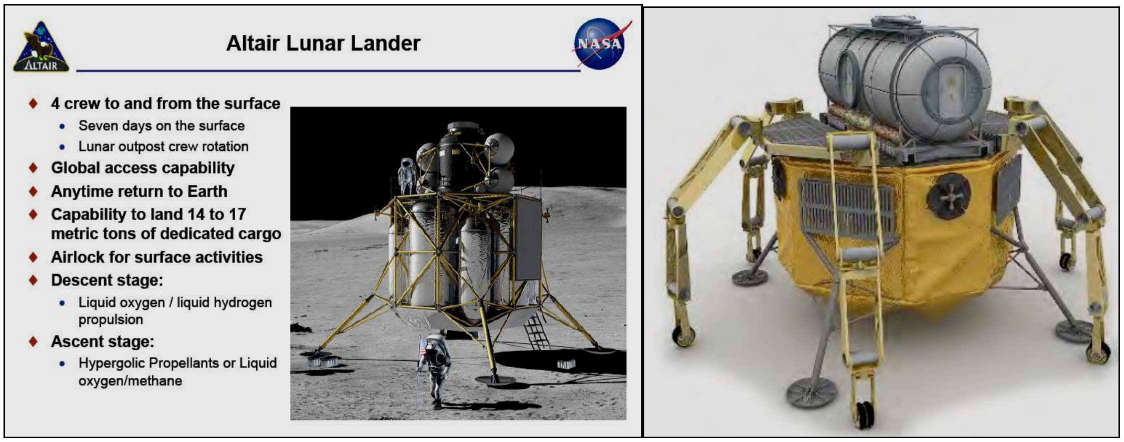
Efficient trajectories usually take longer than fast trajectories. Primary technology options include the tradeoff between efficiency (e.g. low-thrust ion engines) and time (e.g. high-thrust chemical propulsion). The role of high impulse maneuvers becomes apparent when trying to launch from a planetary body above a certain mass; and, when trying to execute a fast maneuver. There is a need for chemical propulsion under certain circumstances. Until processing technology is mature, asteroidal ore transfer is likely to ship unrefined materials to a central processing facility near the customer. Efficient (i.e. minimum energy) transfers will likely use ion or nuclear engines operating in low-thrust configurations. For the lunar and Mars cases, ore transport will likely be accomplished using hauling vehicles.

Transportation of Products from Processing Facilities to Customers

Assuming early-stage asteroid processing facilities are in lunar orbit, at EML-1 or in LEO/GEO, transportation of products to customers will likely use chemical propulsion elements such as a reusable Centaur upper stage. For the lunar and Mars case, a special product hauling vehicle may be required.

Transport up/down Gravity Wells [Moon/Mars]

Mining on asteroids has some inherent problems such as staying attached and remaining in the vicinity. Once the mission is completed however, the departure is no more than leaving for the next location. If the resource of interest is on the surface of the Moon or Mars, the fuel required for operations increases significantly for both the landing [can be aerobreaking on Mars] and for launching on the return. The example below shows a concept of departure from the surface of the Moon.



Altair Lunar Lander

- 4 crew to and from the surface
  - Seven days on the surface
  - Lunar outpost crew rotation
- Global access capability
- Anytime return to Earth
- Capability to land 14 to 17 metric tons of dedicated cargo
- Airlock for surface activities
- Descent stage:
  - Liquid oxygen / liquid hydrogen propulsion
- Ascent stage:
  - Hypergolic Propellants or Liquid oxygen/methane

Figure 5-7, LAT-2 Redesign of Lunar Lander [Neal, 2008].

Transportation of Humans to Settlements

Human transportation is considered to be a primary driver of future propellant sales. Equipment and infrastructure will follow human explorers, expanding capacity and capabilities. Hydrogen and oxygen (decomposed water) remain today’s most efficient chemical propellant. The widespread ubiquity of water and ice in SMR make LOX (liquid oxygen) and hydrogen propellant a likely choice of future space settlers. Because the safety requirements for human vs cargo transportation are very different (cargo can generally take a lot more radiation exposure), high-thrust chemical transportation, or thermal nuclear, will remain a likely choice for getting humans to and from settlements. Transportation architectural designs that surround human passengers with propellant for radiation shielding are commonplace solutions for Mars mission DRMs. Water and/or hydrogen are some of the best forms of radiation protection.

5.1.3 Orbital Dynamics

The moon is three days away from market. Asteroids with low energy transfers can be years to decades away from their customers. Low energy is valuable, but so is time. Transportation energy and time are fundamental principles of terrestrial economic valuation.

> *Many NEAs are relatively easy to reach in energy terms and have very low surface gravities, which would minimize the cost of transferring materials extracted from them to the vicinity of the Earth.* [Crawford, 2013]

Mark Sonter's work on adjusted NPV explains the role of delta-V and time in asteroid valuation. A class of asteroid known as an "easily retrievable object" is now being tracked.

> *"Asteroids and comets are of strategic importance for science in an effort to understand the formation, evolution and composition of the Solar System. Near-Earth Objects (NEOs) are of particular interest because of their accessibility from Earth, but also because of their speculated wealth of material resources. The exploitation of these resources has long been discussed as a means to lower the cost of future space endeavors.* [Sonter, 2012]

The importance of understanding the role of orbital mechanics in asteroid value cannot be overstated.

5.1.4 Earth Delivery of Product

Delivery to terrestrial customers can be accomplished, provided heat shields and steerable lifting bodies are utilized for automated cargo return. Some of the recent work in providing rapid access to ISS for returned (non-human) cargo may directly apply to returning payloads from more distant destinations. Electrodynamic methods for deceleration are beginning to augment more traditional ablative and insulation-based thermal protection approaches. One option that has been examined has been to use SMR for manufacturing heat shields [Hogue, 2012].

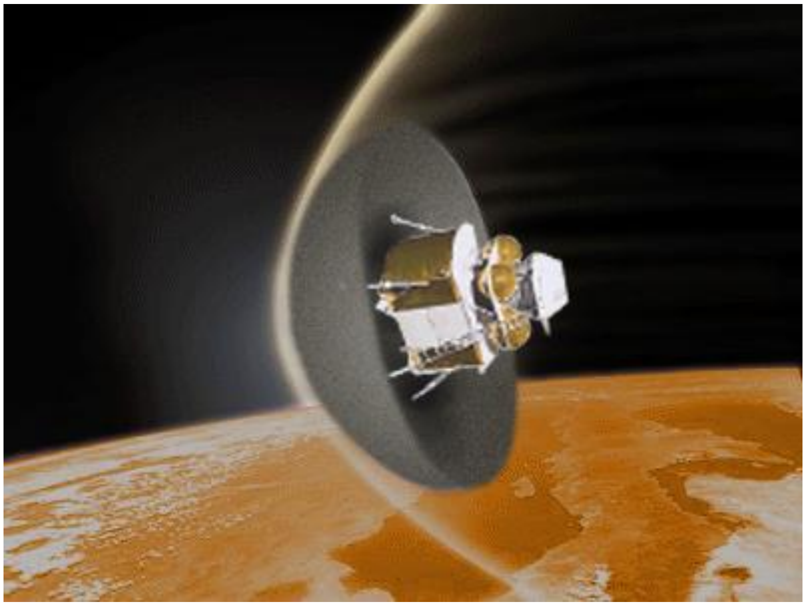


Figure 5-8, Heat Shield Manufacturing with SMR [Hogue et al, 2012].

5.2 SMR Innovative Supporting Systems

There are Future Concept of Inexpensive Transportation Infrastructure for on/off Earth, to include Delivery of Product being pursued. The International Academy of Astronautics conducted a major study, concluded in December 2013, on the Feasibility of Space Elevators; and, approved the findings and recommendations. The major conclusion, from the 41 authors, [Swan, 2013] over the five year study, was endorsed as:

Space Elevators Seem Feasible!

The Academy study delved deeply into all aspects of space elevator transportation infrastructures to include:

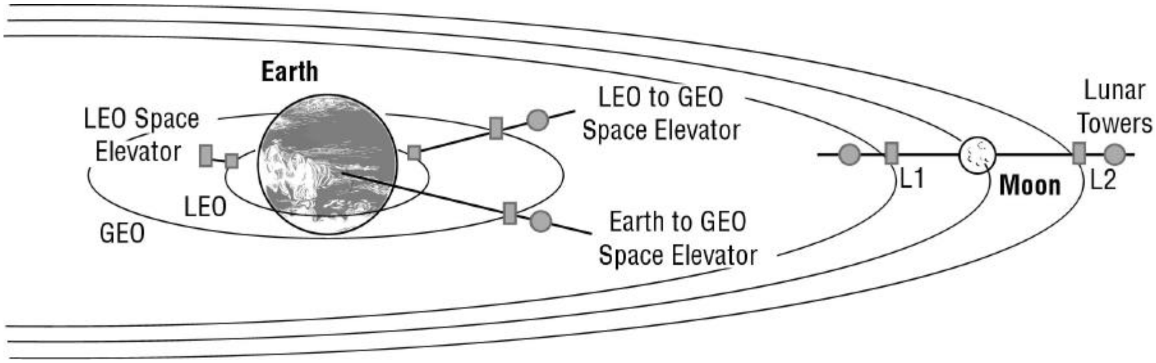
- material development [a concern, but projected for availability by 2030],
- tether deployment and dynamics [shown to be stable with dynamic modes needing to be understood],
- climber design [essentially a traditional satellite without the need for extremely high stress loading],
- operations concept [routine space ops approach],

- hazard protection [space debris was calculated to be an issue; but, it was not a show stopper while atmospheric winds and lightening will require additional engineering solutions], and
- Legal [placement of a complex in the open ocean enables the infrastructure to be both legal and supportable by nation-states].

One scenario inside the report lead to the belief that a space elevator could be developed and operational by 2035 with human transportation within the following ten years. The concept showed that the development of a new space access infrastructure was achievable and desirable. The main attributes of a space elevator would be:

> Low cost access to space [$ 500 (US) per kg to GEO]
> Routine [daily – scheduled, up to seven simultaneous climbers]
> Robust [20 metric ton climber with 14 MT of payload, 6 MT structure]
> Timely [one week delivery to GEO]
> Low stress [elevator like vs. rock & roll of launch vehicles]
> Delivery down to Earth as needed

Understanding the strengths of infrastructures leads to a concept of utilizing both the Earth Space Elevator and a Lunar Space Elevator. The infrastructures work together to provide an up and down avenue for systems components and products. The concept is simple: a rotating body [both Earth and Moon] has a long tether "tossed" out with tension holding it in place [similar to rock over your head being spun around]. As the Earth rotates, each location on the tether is going at a different velocity related to the height of the location. At the surface of the Earth, the tether climber is stationary [really rotating at half a kilometer per second]. At GEO the location is rotating once a day with a horizontal velocity of 3.1 km/sec. As you go above GEO on a space elevator, the horizontal velocity increases such that there is a location, that when released, goes to the Lunar vicinity (or if released higher, it is tossed towards Mars) with very little chemistry needed except at the destination for orbiting. As such, a payload can be loaded onto the space elevator, climb to the Lunar release point, let go on a trajectory towards the Moon, match velocities with a rotating Lunar elevator and then climb down the tether to the Lunar surface – all with minimum fuel. Of course, this works in reverse for delivery of products to the Apex Anchor, GEO or the Earth's surface. The next image shows the concept:



Figue 5-9, Earth and Lunar Elevators inside a transportation infrastructure. [Smitherman, 2004]

The description of both Earth and Lunar space elevators follows. The concept works for a Mars transfer as well, with slight changes to the approach at the destination. Mars space elevators are complicated with the existence of low altitude moons; therefore, rendezvous with Moons of Mars is probably the appropriate approach using chemical rockets or space tugs.

Earth's Space Elevator: For the purpose of this report, the general characteristics for the first few Earth space elevators are:

- Length: 100,000km, anchored on the Earth with a large mass floating in the ocean and a large counterweight at the top end, called an Apex Anchor.
- Width: One meter wide – curved
- Material: Carbon Nano-tubes
- Design: Woven with multiple strands to absorb localized damage and curved to ensure edge-on small size hits do not sever the tether.
- External Power: The power must be external as the gravity well is extreme and lifting your own power is a non-starter. The two concepts being discussed are the use of large lasers pointing up to the climber with a "solar panel like" receiver on its nadir position or fully dependent upon solar energy and large solar arrays.
- Cargo: The first few years will enable 20 metric ton climbers without humans [radiation tolerance an issue for a one week trip] with up to seven concurrent payloads on the tether for the week trip to GEO.

- Construction Strategy: The first space elevator will be built the difficult, and only, way – down from GEO; then, once the gravity well has been overcome, it can be replicated from the ground up leading to multiple elevators around the globe.

The Academy study approach to a space elevator is reflected in the figure below.

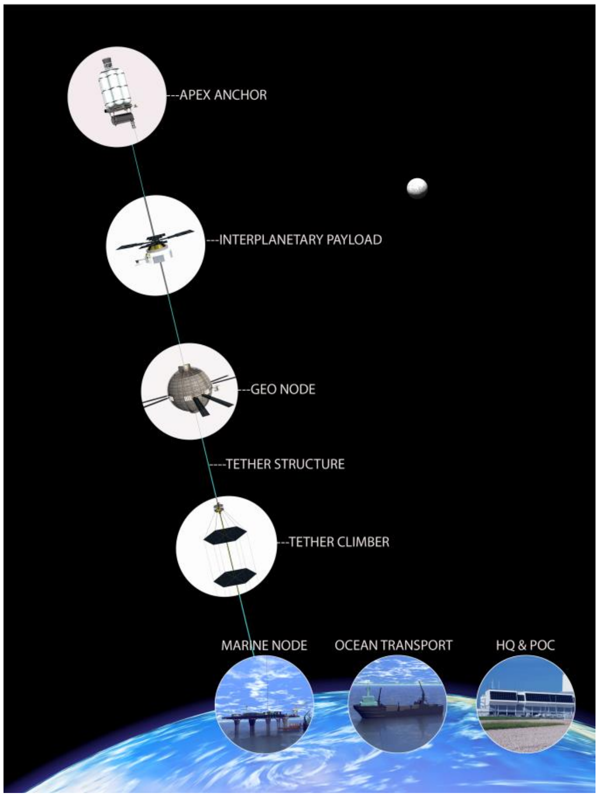


Figure 5-10, Nodal Layout [chasedesignstudios.com]

The keys for leveraging space elevators for mining space mineral resources revolve around several factors:

- The commercial venture will drive prices for access to orbit to well under $500 per kg to GEO when multiple sets of full space elevator infrastructures are in place and operational [3 pairs around the globe].
- Access up will be routine, massive and schedulable.
- Return of product to the surface of the Earth is routine and inexpensive on an elevator vs. rocket return with landing or parachute recovery infrastructure.

- Assembly and initiation of missions can be accomplished at zero-g or low-g either at the GEO station on the space elevator or at its Apex Anchor. Both are "stationary" and can be used as way stations for production processes. In addition, the rotation of the tether initiates launch from it, with its inherent delta "v," without chemical rockets.

The beauty of an operational space elevator for space mineral resource businesses is that it will be a delivery infrastructure that does not throw away climbers, but returns them to Earth [with product] for re-use. The concept should be thought of as a vertical train for space access. To further understand the approach, the following images and discussions represent a future space elevator infrastructure to/from space.

Marine Node: The major aspect of this is the capability to anchor a space elevator to the Earth. The ability to move the base station to stimulate tether motion further up the elevator is required as well as the space/facilities to support operations at this lower node of the space elevator. Two concepts are currently being considered: 1] model after a large oil well derek, or 2] model after a large aircraft carrier.

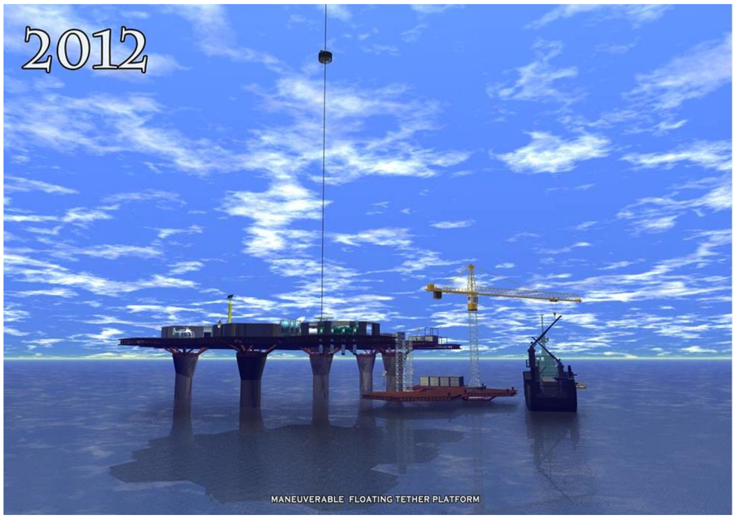


Figure 5-11, Marine Node—Drill ship [chasedesignstudios.com]

GEO Node: This location has been perceived as a very active principle location for major activities on a space elevator. Its basic characteristic would be that the location [at an ideal circular orbit stationary above a longitude line crossing the equator] can support:

- an infrastructure for off-loading and on-loading payload,
- repair of space systems as well as tether climbers,
- refueling of space systems,
- human occupancy, and
- for preparing space systems to go beyond GEO.

One mission that is a natural for the GEO Node is the addition of a fuel depot for the storage and sale of water, fuel and air. The next image shows such a spaceport.

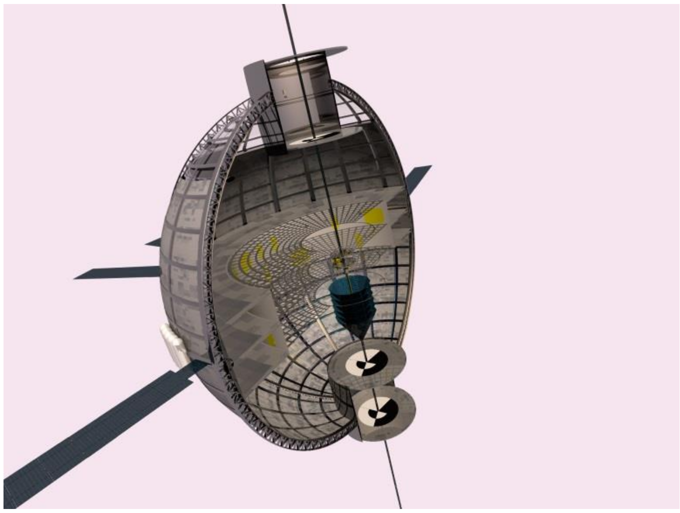


Figure 5-12, GEO Node Work Space [chasedesignstudios.com]

Apex Anchor: This counterweight has long been thought of as a location for discarded hardware or even a captured asteroid for stabilizing tether motion. However, it seems to the current designers of space elevators that the Apex Anchor should be a "smart" location with the active capability to control variations in the tether's dynamics. This would lead to an Apex Anchor with thrusters, computers, and communications nodes. This more complex Apex Anchor could easily start out as the initial tether deployment satellite, in retirement. A natural mission for the Apex Anchor is a depot for accepting SMRs that are to be taken to the surface of the Earth. Massive payloads can be gathered and taken to the GEO Node where they would be transferred to Earth bound tether climbers. This delivery to the surface of the Earth would be safe, easy and take roughly a week – very elevator like. The Apex Anchor would probably look similar to the GEO node structure.

Tether Climber: The tether climber will have many incarnations; from ribbon build-up climber to human transportation once the space elevator has been fully developed and tested. There will be tether inspectors, tether repair climbers, scientific climbers, and, of course, interplanetary missions for climbers beyond GEO. Some major variations in characteristics could even end up with designs related to missions and altitudes [such as return climbers similar to beyond GEO climbers which do not need climber motors, but efficient brakes]. When the mission is the return of large masses of valuable product, such as rare minerals from asteroids, the design will have massive brakes and heat rejection systems with little requirement for solar arrays. Another note, there are no real size restrictions – mass yes – size no. The current concept is six metric tons (MT) of structure which allows 14 MT for payload with the size somewhere around 15 m high and 20 m in diameter.

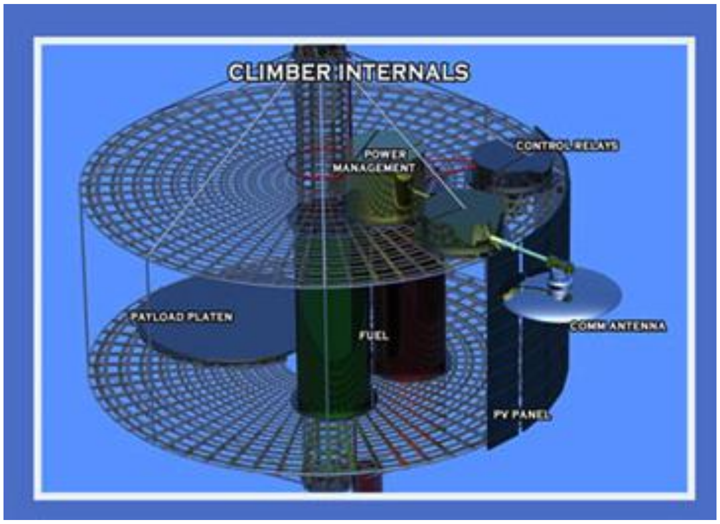


Figure 5-16, Climber Structure [chasedesignstudios.com]

Lunar Space Elevator: The executive summary of the Lunar Elevator study for NASA states that it would be "… a revolutionary method for facilitating development of cis-lunar space." The concept is similar to an Earth space elevator in that it depends upon the rotation of the Moon for the centrifugal force; however, there are other major forces – namely the Earth's major attractive force. The study concluded that a lunar elevator would be stable and would reach beyond the Earth-Moon Lagragian point #1. This development of a highway from the surface of the Moon to a potential spaceport location would enable delivery of lunar material in a very efficient manner. One key is that the forces for the lunar elevator are not as significant as an Earth space elevator and could be designed, executed and operated with today's technologies.

The next figures shows an artist's concept against the background of a lunar topographic map with elevations, consists of a lunar space elevator balanced about the L1 Lagrangian point on the near side of the moon, connected with surface tramways connecting the elevator ribbon with lunar mineral deposits and with ice deposits in craters near the pole." [Pearson, NAIC] In addition, it shows "Robotic vehicles, as shown in the inset, use solar power to carry minerals and propellants along the tramway and up the ribbon to beyond the L1 balance point." [Pearson]

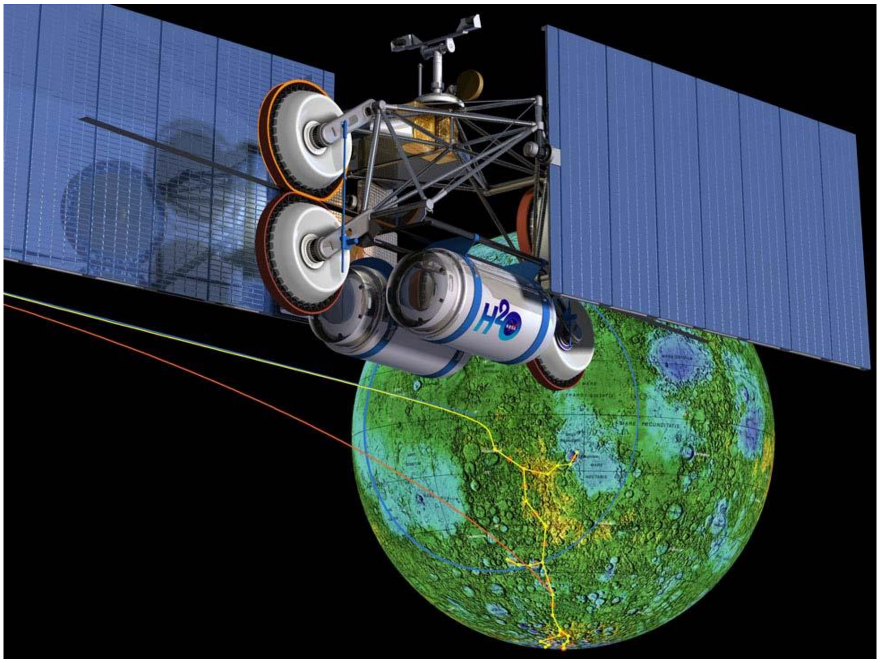


Figure 5-14, Lunar Space Elevator System Concept
[Pearson's 2005]

Vision and Significance

Jerome Pearson, in his NAIC study, recognized the revolutionary approach to transportation within the Earth Moon econosphere. He stated:

"Lunar space elevators will revolutionize the way we operate in cislunar space, and can be a key piece in the development of the Moon and the use of its resources for advanced space development. It can contribute greatly to the new vision for a Moon-Mars initiative by:

5. Providing lunar materials in Earth orbit at less cost than launching from the Earth
6. Providing an unlimited supply of construction material in Earth orbit
7. Providing for continuous supplies to lunar installations
8. Providing the basis of a new paradigm for robotic lunar construction and development
9. Supporting astronomical observatories on the lunar far side"

His conclusions were:

- "The results of this phase I effort demonstrate that the lunar space elevator is feasible, and can be constructed of available materials to fit in the timeframe of the NASA Moon- Mars initiative."
- "The lunar space elevator requires only technology advances commensurate with current plans for return to the Moon."
- It will provide unlimited amounts of lunar material for constructing large solar power satellites and shielded habitats space complexes in Earth orbit."
- With the use of lunar polar ices, the lunar space elevator can also provide large quantities of propellant in Earth orbit for use by vehicles bound for the Moon or Mars."
- The lunar space elevator also provides a low-cost means for transporting infrastructure components from Earth orbit to the lunar surface."

The next figure shows the lunar space elevator.

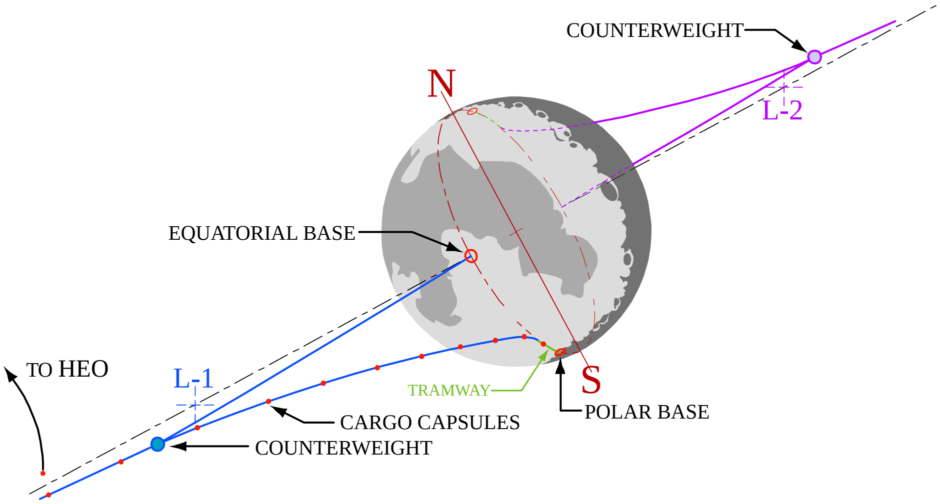


Figure 5-15, Lunar Space Elevators about L1 and L2 [Pearson, 2005]

Notwithstanding the Space Elevator's manifold risks, Mid Earth Orbiting Tethers appear to offer a benefit similar to Space Elevators, although a reusable launch system is required. A MEO tether can potentially get launch costs to below $500/K and can also facilitate returning SMRs to Earth by reducing the reentry velocity by as much as 2-3 km/s from orbit (not escape) velocities. This would enable use of simple ablative heat shields which can be sprayed on at the tether base station. The materials and equipment for such a system are extant, and the navigation issues a less refractory.

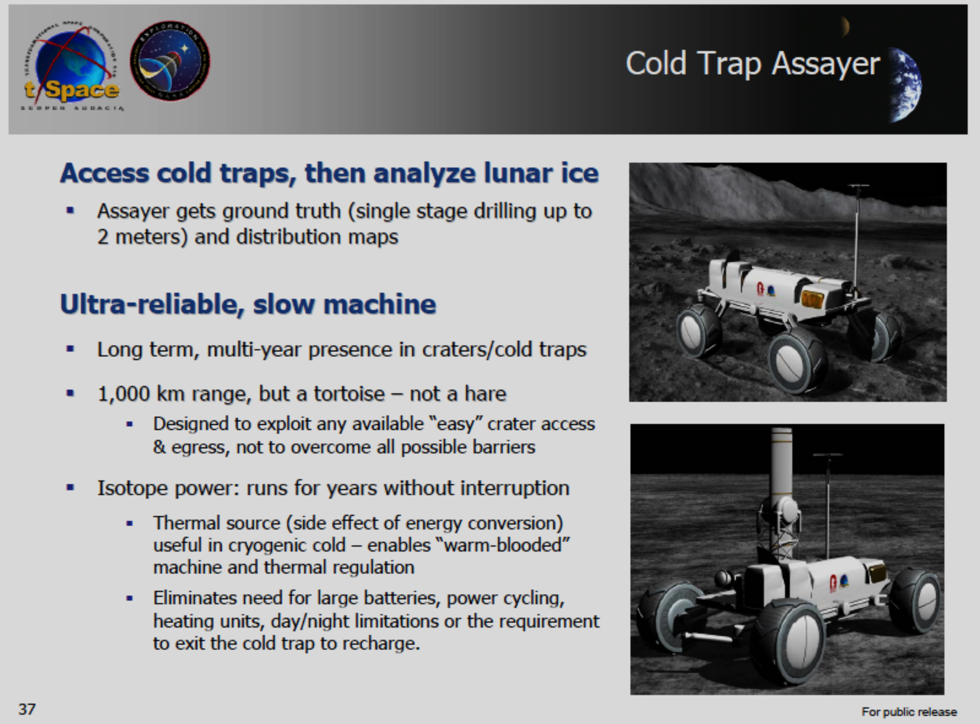
5.3 Generic SMR Functional Architecture

The technical architecture/assumptions and basic systems element types for mineral processing will be described in this section. These segmented technical modules should be capable of meeting the demand scenarios above. This section will cover a spectrum of SMR operations; such as: prospecting, resource extraction, materials handling and transport, resource processing, space manufacturing, space construction, and product capture, storage, refining and distribution.

5.3.1 Identification

Because only 10,000 of the estimated more than two million near Earth asteroids (NEAs) have had their trajectories charted, an important element of prospecting will be the identification of the as-yet-unseen millions of potentially valuable objects. The vast majority of the 10,000 have limited knowledge. As a result, the next steps include both finding more NEAs and finding out more about them.

A lunar polar prospecting / ground truth program has been repeatedly proposed as an enabling & risk reduction step NASA could undertake to help future commercial enterprises - it remains a really good idea.



Cold Trap Assayer

Access cold traps, then analyze lunar ice

- Assayer gets ground truth (single stage drilling up to 2 meters) and distribution maps

Ultra-reliable, slow machine

- Long term, multi-year presence in craters/cold traps
- 1,000 km range, but a tortoise – not a hare
    - Designed to exploit any available "easy" crater access & egress, not to overcome all possible barriers
- Isotope power: runs for years without interruption
    - Thermal source (side effect of energy conversion) useful in cryogenic cold – enables "warm-blooded" machine and thermal regulation
    - Eliminates need for large batteries, power cycling, heating units, day/night limitations or the requirement to exit the cold trap to recharge.

For public release

Figure 5-16, Lunar Cold Trap Assay Vehicle [tSpace, 2005].

Indeed, the Chinese lunar surface mission did break new ground by becoming the first rover to visit the Moon since 1976. Prospecting data collected will no doubt enable future commercial enterprises.

Figure 5-17, Testing the Chang'e-3 Lunar Rover (courtesy Space.com).

5.3.2 Resource Extraction

Extraction or severance of the SMR from its native environment is the first required step in a process that will result in a useful end product. Excavation is the most common method of extraction used on Earth today – a typical front-end loader is a good example. Due to the need to apply reactive forces during the excavation process (pushing a blade or scoop into the ground requires some kind of grip), anchoring systems for lunar and asteroid regolith should also be included in this category. For the Moon and Mars, excavation systems are straightforward due to the unconsolidated nature of much of the surficial material. For asteroids, basic variables for excavator design include resource type, spin rate, specific gravity, percent fragmentation and grain size distribution. Planetary surface excavation capabilities have already been demonstrated on the Moon and Mars - specifically the scooping of regolith samples for transfer to a sample return canister (the Russian Luna 24 mission) or scientific instruments (the US Viking and Phoenix Mars missions). In addition, coring of lunar regolith samples was done during the Apollo missions, while grinding and analysis of rock samples have been done on a number of Moon and Mars missions. Preliminary work has been performed on acquiring and separating oxygen from Mars atmospheric CO_2, as well as separation/filtration of dust during Mars atmospheric processing [Sanders, 2005].

5.3.3 Materials Handling & Transport

Materials transportation systems commonly used in mining include haul trucks, conveyors and rail cars. Handling equipment is typically related to the input and/or output sides of the above options. For example, a haul truck typically dumps its load into a crusher, and the conveyor discharge ramp can be an excellent place for electrostatic or magnetic separation or size classification using a grizzly grid (an oversized sieve). Examples of specialized SMR materials handling systems include the possible use of magnetic raking for asteroid PGMs, as well as hydro or air cyclones for separations in microgravity. Extraterrestrial experience in lunar materials handling and transporting includes the Apollo sample collection, raking and storage/containment devices. Mars samples have been robotically manipulated for limited analysis and disposal by the Viking, MER, Phoenix and MSL missions.

5.3.4 Resource Processing

A wide variety of mineral processing techniques are in use today providing feedstock to the global manufacturing infrastructure. Many of the chemical and physical separation and refining methods in use today on Earth will map directly to use in space – simplifying the need to find a feasible process. The most efficient (optimal, which is better than feasible) means of SMR processing will likely take advantage of, or leverage, the unique environments found in space, creating competitive advantage for the company or agency that discovers and patents it. An example of this is the use of the Mond or Carbonyl process for nickel and iron extraction and vapor deposition, a low temperature, microgravity-friendly process that utilizes carbon monoxide as its working fluid. The vast majority of near-Earth asteroids have abundant Iron, nickel and carbon, making this an ideal candidate process for SMR application.

Lunar ISRU has a 30-year history of laboratory testing with little systems-level development. The successful production of oxygen from returned Apollo lunar regolith samples has been demonstrated using the hydrogen reduction process. Several prototype systems for Mars atmospheric processing demonstrated oxygen and oxygen/methane production. Laboratory demonstrations were performed for more advanced Mars surface hydrocarbon fuel production including methanol, ethylene, benzene/toluene, and short-chain hydrocarbon mixtures.

Materials processing demonstrations were done in microgravity on a number of Apollo, Skylab, and Spacelab experiments [Sanders, 2005].

Common industrial feedstock can be found in asteroid, lunar and Martian regolith. The Moon is rich in metals (Fe, Ni, Al, Ti, Si - even Ca is an excellent conductor as long as it remains in vacuum) as well as glass that could be spun into fibers. Viking data shows the same metals may be available in the Martian regolith, thus space metal production and refining technology could apply to the Moon, Mars and even asteroids. A number of lunar regolith oxygen production technologies that been demonstrated at the laboratory scale leave behind pure metal in the spent regolith slag. This is due to reducing metal oxides (typically Iron) to liberate their Oxygen for use in space transportation. However, to date no laboratory-scale experiment has actually separated pure metal from the remaining slag [Sanders, 2005].

Some biological processes could be valuable for SMR processing applications. Bioreactors for extraction of materials and synthesis of products are becoming commonplace on Earth, and could be candidates for low power consumption SMR processes. NASA has even studied the use of synthetic biology to produce organisms that could process asteroid or planetary surface resources into useful products.

Recycling of reagents will be likely for early SMR development due to the high anticipated cost of terrestrial resupply. The use of local materials for reagents (such as the use of hydrogen or carbon as a reducing agent) and catalysts will also be rewarded by reducing dependence on Earth resources.

5.3.5 Space Manufacturing

Raw metals have little utility in space; yet, combined with modern manufacturing and 3D printing technology could ignite a revolution in space capabilities. Paper studies suggest that 90% manufacturing closure could be obtained from the use of lunar materials, and nearly 100% from Mars materials [Sanders, 2005]. Asteroid materials hold similar promise. In-space fabrication and repair has been examined by NASA for its ability to reduce mission risk (particularly for human Mars exploration) and provide flexible repair options, reducing the need for redundancy and spares. A long series of space manufacturing conferences were spawned and hosted by Princeton University professor Gerard O'Neil's Space Studies Institute. A rich history of space manufacturing systems design, costing and evaluation is recorded in their archives. The tendency to think big was much stronger in the post-Apollo era (the early 1970's) than it is today. Many ideas from that era should be re-evaluated today from an economic and business perspective. Translating those concepts into the language of markets, costs, engineering feasibility and customer demand would enable access to the capital needed to build these bold systems.

5.3.6 Advanced Manufacturing Will Enable New Space Markets

The revolution in 3D printing is accelerating the growth of automated manufacturing technology while drawing the attention of the investment community into a new set of commercial products, services and capabilities. Space mineral resources stand to reap the rewards of investment as this largely private development effort produces new tools for turning raw materials into finished products. Indeed, low gravity is anticipated to offer an ideal environment for increasing the scale of manufacturing by one or more orders of magnitude vs. conventional systems in use today. The system offered will depend upon robust in-situ space power (solar or nuclear) combined with material feedstock such as scavenged orbital debris or asteroidal resources and will, therefore, contribute to the emergence of a larger economy.

Technology for in-space additive manufacturing and robotic assembly will enable many new commercial markets, including remote systems repair and refurbishment, the ability to create new value from space debris, repairing ISS components, remote satellite reconditioning, rocket motor reconditioning (new thrust chambers can be made using laser sintering of powdered metals), the creation of large-scale space structures in LEO and GEO, and even enabling in-space manufacturing of high-mass space solar power system elements (structural support and heavy mechanisms). The ability to repair, build and assemble spacecraft, satellites, telescopes and other devices in space has been underway for some time. The Russian MIR program, as well as the current International Space Station, offers a rich set of well-documented examples of how to do construction and assembly in microgravity.

Manufacturing capabilities on planetary outposts will depend upon SMR for their input feedstock.

5.3.7 Space Construction

Space manufacturing is a necessary element of what could become an enabling emergent capability: The ability to construct habitats and industrial infrastructure in orbit and on planetary surfaces. This is the key to the independence of future space settlements and industries; and, holds the promise of expanding the sphere of human influence orders of magnitude beyond its current resource and spatial limits.

Lunar and Mars multispectral imagery and topographic data sets are steadily increasing in resolution, enabling preliminary site planning for important early settlement targets such as the highly illuminated lunar polar regions or “peaks of eternal light”. Geophysical characterization (the key to stable foundations) is available at certain lunar and Martian sites as well as a growing list of asteroids. Most proposed space habitat construction methods have well-characterized terrestrial equivalents. Laboratory tests on lunar and Martian construction material fabrication includes sulfur and water-based concretes, glass fibers and rods, sintered bricks, and making more complex shapes using combustion synthesis [Sanders, 2005].

Early lunar and Martian construction efforts are likely to focus on landing site preparation and radiation protection. The Apollo landings unleashed a torrent of entrained particles that sandblasted everything in their path. The Surveyor 3 spacecraft was the only victim of this, and provides an important data point for this phenomenon. Pavement or bricks as well as flow channeling will be required in order for multiple landings to be accomplished at the same site.

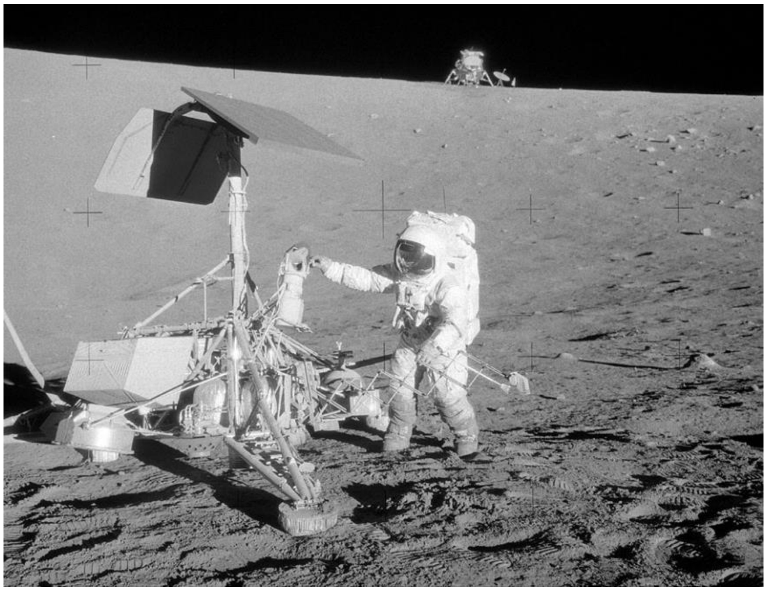


Figure 5-18, Surveyor 3 Visited by Apollo 12 crew [image NASA].

Radiation protection will leverage SMR. A number of designs exist for burying early lunar habitats using raw or sandbagged regolith in order to protect crew from solar proton events.

5.3.8 Product Capture, Storage, Refining & Distribution

Capture of volatile gases is another important enabling SMR process technology. This could be done using adsorption by porous media, condensation on cold plate, or creating a pressure differential and using compression. Yet capture is far from sufficient. Mixed volatile separation will be needed (especially if lunar polar volatiles are mined as ices), requiring refining &/or distillation technology. After that, storage and distribution systems will be required, including fluid couplings for transfer of liquid or gaseous products to fuel cells or vehicles needing refueling. Fortunately, plenty of terrestrial cryogenic fluid management experience exists, including the potential for COTS solutions that could apply directly to space.

Waste heat dissipation is an important part of current spacecraft design, where thermal management issues can become complex due to sun angles and shadow. Indeed, radiator failures are a common problem in space. Thermal management issues limited the performance of at least one of the Apollo lunar rovers. Limited capacity cryo-coolers have flown in space supporting science instruments including infrared cameras. Cryogenic fluid storage systems have flown in space, but for limited durations and (as of 2005) none with integrated liquefaction systems. Automatic and EVA fluid couplings have flown on the ISS; and, a helium II fluid coupling was built but not flown [Sanders, 2005].

5.3.9 Asteroid Capture

The ability to capture, attach to and stay close to are challenging to a space system approaching an asteroid. NASA has awarded a contract to study this approach in more detail. The press announcement is:

> "Bothell, WA, 10 June 2014 – Tethers Unlimited, Inc. (TUI) announces that NASA's Innovative Advanced Concepts (NIAC) Program has selected it for award of a Phase I contract to develop the "Weightless Rendezvous And Net Grapple to Limit Excess Rotation" (WRANGLER) concept for capture and de-spin of asteroids and orbital debris.
>
> "NASA is currently considering the pursuit of an ambitious mission to capture a small near-Earth asteroid and maneuver it into orbit around the moon for scientific study and possibly mining for resources. A challenge for this "Asteroid Redirect Mission" (ARM) is the fact that most asteroids that are small enough to be retrieved are rotating relatively quickly, and may be surrounded by a cloud of dust particles, making the capture maneuver very challenging and risky for the ARM spacecraft.
>
> "The WRANGLER concept combines two relatively simple technologies – a lightweight, deployable net that we originally developed to for capture of orbital debris, and a small tether deployer – to enable a very small spacecraft to latch onto a tumbling asteroid and then de-spin it," said Dr. Rob Hoyt, TUI's CEO and Chief Scientist. "The tether can be tiny, about as thin as dental floss, but if we deploy several miles of it between the asteroid and the nanosatellite, the tether provides incredible 'leverage' to enable a nanosatellite weighing just 22 pounds to de-spin an asteroid massing 1,000 tons. Fractionating the ARM mission architecture by using a small nanosatellite to capture and de-spin the asteroid and then using a space tug to tow the object to lunar orbit could reduce risks to the mission and significantly reduce overall mission costs."
>
> "Under the NIAC funding TUI will use its high-fidelity simulation tools to investigate the feasibility of the WRANGLER concept and begin planning a demonstration mission that could test the

> WRANGLER idea by capturing and de-tumbling a piece of space debris, and then use TUI's Terminator Tape technology to remove the debris from orbit."

5.3.10 Power Generation

One of the first requirements for any exploration is sufficient power at the needed location. Once prospecting is over and extraction, processing, manufacturing, and transportation activities dominate, the power needs will be great. Initially, in-situ resources will be leveraged for power generation; but, as demands grow, other sources of energy will be used.

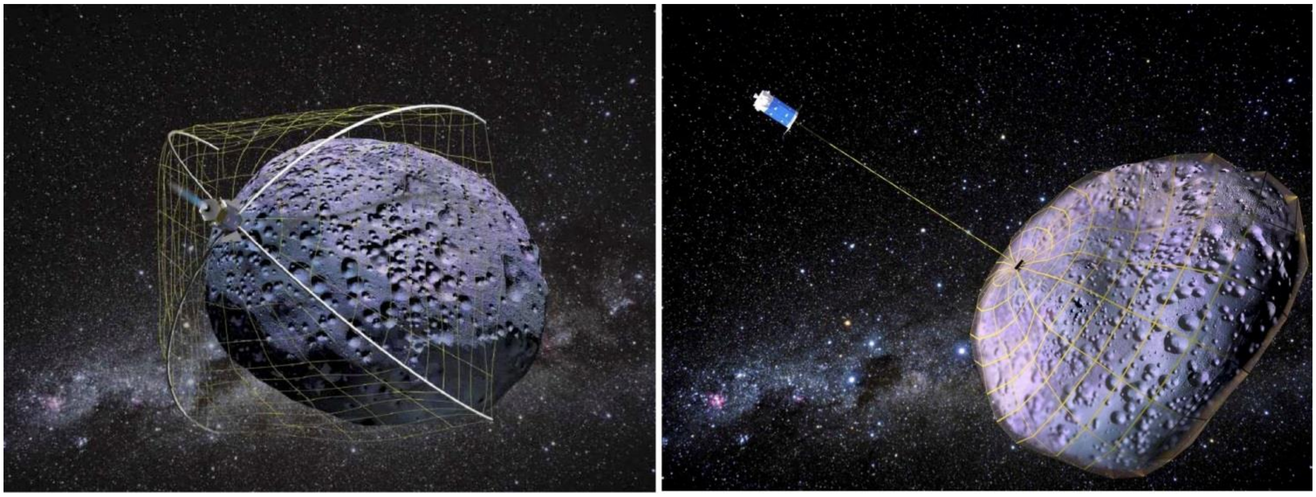


Figure 5-19, WRANGLER system - Asteroid Capture [Tethers Unlimited]

5.4 R&D Goals and Objectives

Capabilities are an emergent property of a nested set of technologies that work together to provide new options.

> *"Capabilities are the foundation of NASA's new approach, and of future human space exploration. Each capability provides a specific function that solves an exploration challenge, and in combination with other capabilities, it will advance human presence into our solar system. NASA identified a set of capabilities that are essential to exploring cis-lunar space, NEAs, the Moon, and Mars and its moons. These capabilities provide transportation to destinations, enable operations in space and at a destination, and provide habitation and destination-specific systems for exploring our solar system."* [Olson, 2012]

From this perspective, capabilities are much more valuable than technologies alone. An analogy can be drawn from SMR-derived industrial feedstock. While raw materials will have great value in the future settlement of space, they do not have real value or purpose until something useful is manufactured or created from them. A short list of lunar SMR-related capabilities was created by the NASA in-situ resource utilization (ISRU) capability road mapping team in 2005 as shown below.

> *"The list below covers the highest priority gaps that need to be addressed before ISRU can be utilized effectively in future human missions.*
>
> - *Dust mitigation techniques to prevent hardware wear and life issues*
> - *Reduced-gravity effects on solid material handling, processing, manufacturing, and construction*
> - *Definition of Moon and Mars water and resource extraction, handling, & transportation technologies and capabilities for the Moon and Mars environment*
> - *Development of seals that can work repeatedly in a low temperature, high vacuum, abrasive dust environment. Processes to produce oxygen and manufacturing and construction feedstock from regolith*
> - *Tele-operation and/or automation of robotic excavation, transportation, and construction processes*
> - *Dust mitigating fluid couplings and leak detection in open vacuum or low atmospheric environments*
> - *Mass, volume, and power efficient cryogenic storage and distribution systems*
> - *Resource prospecting instruments and ISRU control sensors*
> - *Modular, highly flexible, and compact manufacturing techniques for in-situ fabrication & repair*
> - *Development of power generation, management, and distribution from in-situ resources and feedstock"* [Sanders, 2005]

These capabilities remain high-priority R&D targets today. They will depend upon a series of technological breakthroughs – many of which might be found in today's vast and complex industrial infrastructure simply by creating innovative partnerships and outreach. It is critical to remember that SMR physics is different than terrestrial mining and manufacturing physics. A physics-based *research* program identifying similarities and differences should be started immediately. The goal should be finding novel approaches &/or to stimulate the *development* of new technologies and capabilities. Side benefits would include spinoffs that could stimulate many industries on Earth.

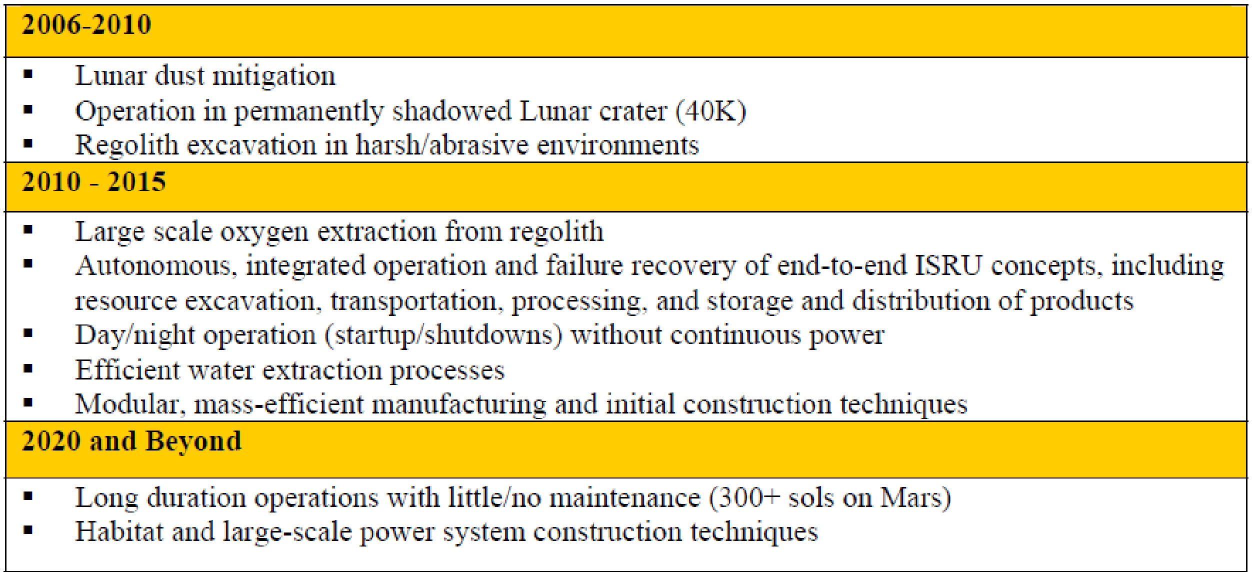
More is going to be learned by going to the space resource site than by thinking about it while safely within a terrestrial lab or think tank. Hands-on experience is desperately needed. Novel technologies require immersion and access to the new environment. The unknown unknowables offer the fastest path to discovery and innovation. The first parties to get to SMR will likely develop the key patents – creating positive feedback for those who like to compete.

5.5 Opportunity Summary

It is time to re-think risk for space. True risk perceptions and preferences are being revealed by a growing queue of competitive Mars settlers, entrepreneurs, and billionaires entering the new-space race. One way to interpret the difference between NASA's risk preferences and those of future Mars settlers is growing confidence in follow-on infrastructure and support systems naturally available through commercial models. In general, higher costs are accepted by industry in order to buy down systems risk – offering important data points from which to model future systems. Maintenance and refurbishment are significant game-changers for space infrastructure development and support – offering a fundamentally different cost structure than heritage-based expendable systems. Refueling is also a game-changer for transportation system costing and operations – linearizing the rocket equation and radically extending the reach of current assets.

Government and Commercial Capability Opportunities

The following list of flight demonstrations was recommended in 2005. Many of these could be adopted and completed by private agents, creating a strong portfolio of patents.



2006-2010

- Lunar dust mitigation
- Operation in permanently shadowed Lunar crater (40K)
- Regolith excavation in harsh/abrasive environments

2010 - 2015

- Large scale oxygen extraction from regolith
- Autonomous, integrated operation and failure recovery of end-to-end ISRU concepts, including resource excavation, transportation, processing, and storage and distribution of products
- Day/night operation (startup/shutdowns) without continuous power
- Efficient water extraction processes
- Modular, mass-efficient manufacturing and initial construction techniques

2020 and Beyond

- Long duration operations with little/no maintenance (300+ sols on Mars)
- Habitat and large-scale power system construction techniques

Figure 5-20, Flight Demonstration Mission List
For NASA's ISRU Program [Sanders, 2005].

Expanding this list to incorporate space-settlement related capabilities would add:

- Construct commercial habitats in space to support significant populations
- Put robots into space that can help people multiply their work effort
- Stage growth using autonomous systems, followed by people
- Develop asteroid mining and impact risk mitigation technologies
- Develop methods of value added processing for raw materials
- Develop life-support technology & closed loop systems
- Develop bionomics informed spacecraft that can self-repair and live off the land
- Develop genetic and synthetic biology technology for mineral processing and life support applications
- Demonstrate advanced greenhouse technology for space food and animal production
- Advance radiation protection systems, including superconducting shielding
- Investigate commercial opportunities related to transcending human & biological limitations to living in space

- Find and develop better ways to create electricity in space, including space solar power systems, nano-antennas, lasers and rectennas for power collection and distribution
- Develop better batteries & storage technology
- Demonstrate and perfect VASIMR for 15,000 sec of impulse, extend plasma thrusters into high-thrust areas
- Create remote civilization nodes based upon / supported by mineral production and agriculture that offer an insurance policy against planetary disaster

The list above will facilitate and reward commercial investment – a process that is well underway. Examples include SpaceX, Bigelow Aerospace, Golden Spike and Blue Origin. It will also engage the best and most advanced minds in research labs worldwide.

5.5.1 Human-Tended System Servicing

At its core, the impulse to settle space is the expansion of the human sphere of influence into the solar system. Design for assembly, maintenance and servicing will embrace the ability for humans to access and repair or upgrade hardware. Robots will not always be available for these tasks, nor will their well-being depend upon critical functions.

Figure 5-21, Hubble Servicing Mission [NASA STS 125].

5.5.2 Automated Assembly, Maintenance & Servicing

Applications of advanced industrial tele operated maintenance technologies are ideally suited for maintenance and servicing of lunar base elements and SMR systems. This is due to minimum communication delays between the Earth and Moon (estimated at just under 2 seconds round trip). Increased automation levels for maintenance and service will be required as the teleop delay times increase. Given the 40 minute delays with communications to Mars spacecraft, they require a much higher level of automation, thus computational, memory, sensor and software complexity. Platforms for tele operated and automated maintenance and servicing currently exist in the DEXTRE robot originally built by MDA for a Hubble Telescope servicing mission. It was later deployed to ISS for inspection and maintenance. Another system under development at NASA is the Robonaut device under a partnership between JSC and General Motors. Maintenance and repair can be largely tele operated today, and with growing on-orbit experience, progressively automated. The use of plug-and-play standards for interfaces and subsystems will further streamline maintenance.

> *"Launched in 2008, MDA's Special Purpose Dexterous Manipulator (SPDM), also known as Dextre, became the world's first on-orbit servicing robot. Under contract to the Canadian Space Agency, the company was the prime contractor for the development of Dextre as part of the Mobile Servicing System, Canada's contribution to the International Space Station. The Mobile Servicing System comprises Canadarm2, the Mobile Base System, and Dextre."* … *"This extremely advanced, highly dexterous dual-armed robot carries out delicate maintenance and servicing tasks on the International Space Station. Tasks include installing and removing small payloads such as batteries, power supplies and computers, operating robotic tools such as specialized wrenches and socket extensions for delicate maintenance and servicing tasks, providing power and data connectivity to payloads, and manipulating, installing, removing, and inspecting scientific payloads."* [MDA, 2013]

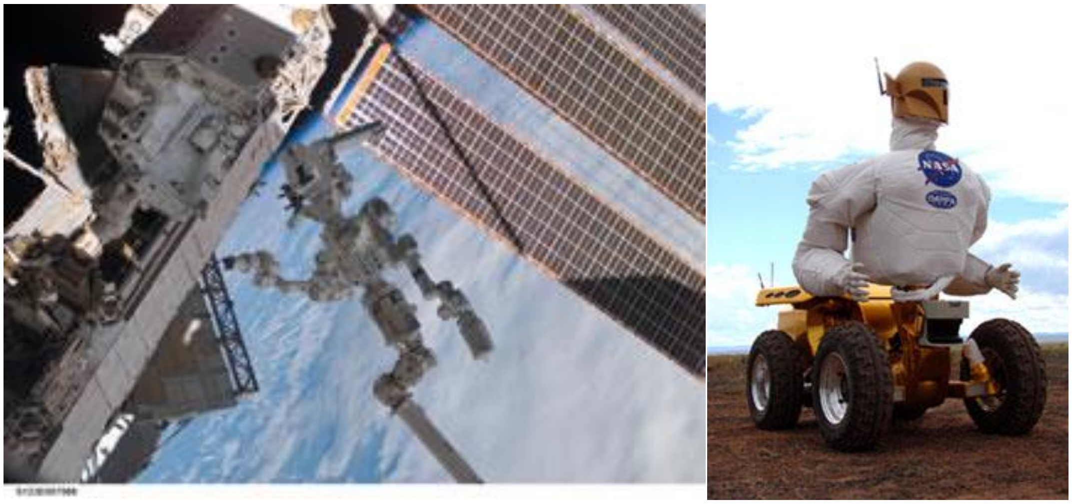


Figure 5-22 MDA DEXTRE Robot on ISS [MDA, 2013] and JSC Robonaut .

The adaptation of tele operated robotic platforms designed for the ISS, lunar, and Mars surface maintenance, as well as SMR support operations, is currently underway. Extensibility of current technology into planetary surface uses has long been a NASA goal.

> *"Centaur 2 was delivered for a "shake out cruise" at the Desert Rats 2010 field test in August 2010. Fitted with a digging implement developed by the HRS engineers working at GRC, Centaur 2 was shown to be a rugged and agile new rover. The Robonaut 2 torso has now been integrated as a new payload, and integrated with the electrical and data systems of the Centaur 2 rover. Combined, this new mobile manipulation system was integrated in time to support KSC launch activities of the Robonaut unit R2B on STS -133. Future lower bodies for the Robonaut 2 series include zero gravity climbing legs for performing EVA tasks on the ISS."* [JSC, 2013]

5.5.3 Space based Use Interface Systems

The use of common international interfaces for SMR will enable interoperability across systems. For example, common standard interfaces for propellant transfer, power and docking will enhance safety and enable cross-platform and multi-national use of emplaced space infrastructure. In general, there has been an industry-wide migration from ad-hoc government standards to open standards.

> *"The space industry has been moving from a period where government standards (US Military Standards (MilStd), NASA standards and even Russian GOST standards) were dominant (pre-*

> *1990) to international (International Organization for Standardization (ISO), Consultative Committee for Space Data Systems (CCSDS)), regional (European Coordination for Space Standardization (ECSS)) and professional (AIAA) industry standards (post-1992). CCSDS originated as a committee of and for the national space agencies of the world, but today is coupled with industry through ISO. The AIAA, CCSDS and ISO are the dominant SDOs for US markets."* [Slane, 2012]

The role of open standards could be enabling in space mineral resource (SMR) utilization, lunar settlement and space commercialization. The International Standards Organization (ISO) has created a placeholder for this development.

> *"SC14 emphasizes terrestrial and non-terrestrial market application services including*
>
> - *Satellite communications*
>   - *for education and health*
>   - *for logistical support*
> - *Remote Sensing*
>   - *Earth environmental surveillance and protection, including protection against infectious diseases*
>   - *Earth management of natural resources (e.g., energy and water)*
>   - *scientific investigation*
>   - *space exploration*
>   - *space surveillance (against orbital traffic, natural objects)*
>   - *intelligent roads*
>   - *sustainable development in mountainous areas*
>   - *maritime surveillance (against piracy, border security, supply chain safety)*
> - *Disaster response and management*
>   - *natural and man-made disaster response*
>   - *orbital debris management and mitigation*
> - *Navigation*
>   - *global (centimeter scale driven by agriculture)*
>   - *space navigation*
> - *Manned Systems/Tourism*
> - *Others"* [Slane, 2013]

The conclusion that arises when looking at all the efforts across the space arena over the last five years is:

An SMR commercial venture can be accomplished with rocket and mining technologies available today!

One key is that each mining operation on the Moon, Mars, and several potential NEAs will require tremendous planning, extraordinary testing (on Earth and in orbit), significant funding and commercial corporate commitment to a revolution. The resulting mining operations will be bold, innovative and tremendously rewarding when accomplished!

Part B – Assessment of Technologies of Readiness, Utilization, and Identification of Risks.

5.6 TECHNOLOGY READINESS AND RISK ASSESSMENT

This section will identify primary SMR-related technologies and risks, and offer suggestions regarding how to assess them. Primary classes of risk include technical, systems, operational, economic, human health and international law & policy. Many of these risks are correlated – some positively and some negatively. A rigorous and quantitative statistical approach to risk assessment and modeling will be outlined, with details left to later investigators. This portion of the chapter is intended as a general introduction to technology and risk as well as how they are interrelated.

SMR technology and capability development is an important tool for reducing many classes of space settlement risk. Human exploration risks have been sharply reduced since the Apollo era due to rapid aerospace technology advances, as well as a steady stream of scientific discoveries about the asteroids, Moon and Mars. Public, private, and international partnerships can reduce risk on both sides if crafted with care and proper attention to creating a reward system that maximizes benefits. An example of this is the potential reduction of asteroid impact risk (a civilization-ending threat) by partnering with one or more private asteroid mining companies. Risk assessment and mitigation is critical in most terrestrial industries, often involving a public aspect that is either restrictive or enabling. Reduction of industry specific risks is often framed as an economic investment with a very clear payoff - the weighted average cost of capital is lowered, increasing the net present value of a project.

Technology maturation is a well-understood process in aerospace that steadily reduces technical and mission risk for a given cost. An economic model can directly measure the benefits of investment in technological improvements as long as their technical influence on results are well understood (for example switching from chemical to nuclear thermal propulsion). Exploration expenditures reduce resource or geologic risks in the mining industry, trading increased certainty about orebody variance and structural confinement for an auditable drilling and sampling process.

The Apollo Program provides a powerful argument that "new technology" is not actually a requirement for human lunar access – this is the primary argument behind the principle of heritage in design. Development of new technology is neither necessary (old technology will work although it may suffer from inefficiency) nor sufficient (as evidenced by our current inability to return humans to the Moon). Advanced technologies "needed for human space access" have become the rationale for a growing portion of NASA's budget. SMR is a different story – a significant amount of new technology will be required to implement it. Detailed descriptions of SMR technology are not the main focus of this chapter. Instead, generalizations can be made regarding SMR technology classes. Note the importance of having a mining technological background as much as aerospace in the search for methods and modalities that enable SMR.

Ultimately, technology and capability maturation requires immersion, as well as direct access to the space mineral environment (whether it is a fast-spinning asteroid or a lunar polar crater floor). This is the only way to discover the unknowable unknowns which are the hidden show stoppers or enablers. The first entities (public or private) to get there and try new approaches are likely to develop the key patents due to the hit-and-miss process of research and discovery. Indeed, the more mistakes or technical risks that are taken, the higher the rate of potential learning will be. The first to get there will capture a lion's share of the rewards – which could ignite a commercial space race.

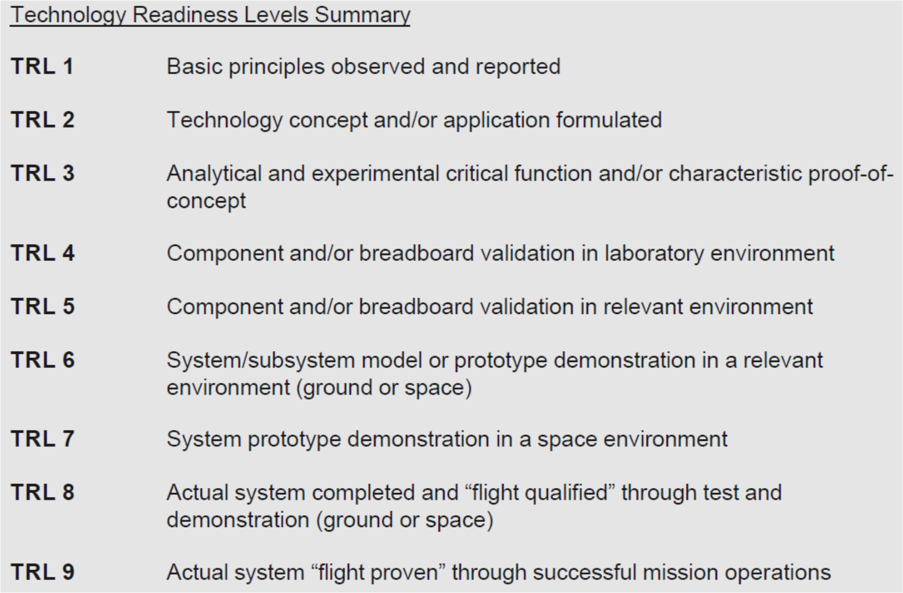
Risks often hide opportunity. Systematic risk assessments provide mechanisms for identifying risks that actually represent opportunities, and which represent show stoppers. The risk assessment process can provide a clear view of key variables or leading indicators to spot the difference. A good risk assessment is founded on an organization's risk appetite and tolerance, providing a basis for predicting risk responses. Public entities generally have much higher risk aversion than private ones (although there are a few notable exceptions such as DARPA).

5.6.1 Assumptions and Methodologies

Technology and risk are intimately connected. A common industrial perspective on technological investment is that it buys down or reduces system, component or process risk. The mining industry invests in mineral exploration (a form of scientific data collection using drills, sampling and assay methods) in order to reduce resource risk as well as to increase confidence in an ore body's economic value through auditable methods. A blend of methodologies from the mining and aerospace industries will be used to evaluate SMR technology and risk.

The NASA Technology Readiness Level (TRL) Standard

The NASA-developed Technology Readiness Level (TRL) system will be adopted for the purposes of this study. It is well understood and practiced internationally. The maturity of required technologies for SMR will be rated or reported using this system.



Technology Readiness Levels Summary

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL 9	Actual system “flight proven” through successful mission operations

Figure 5-22, NASA Technology Readiness Level [Mankins, 1995].

The TRL rating system is useful for evaluating both technology and capability (a nested set of technologies) maturity, and is often helpful in estimating costs and risks for completion or full implementation of systems using novel technologies.

Risk Assessment and Mitigation Methods

Space settlement and SMR risk assessments will utilize a blend of risk management and reporting practices from aerospace, mining and finance. Risk assessment is a systematic process that identifies and evaluates potential events that affect the achievement of goals and objectives. Such events can be external (macroeconomic variables, the regulatory landscape, and emerging competition) or internal (process, infrastructure, hardware and software). When there is a probability that events will intersect with objectives, they become risks. Risk can be defined as **“the possibility that an event will occur and adversely affect the achievement of objectives”** [Atkinson, 2008].

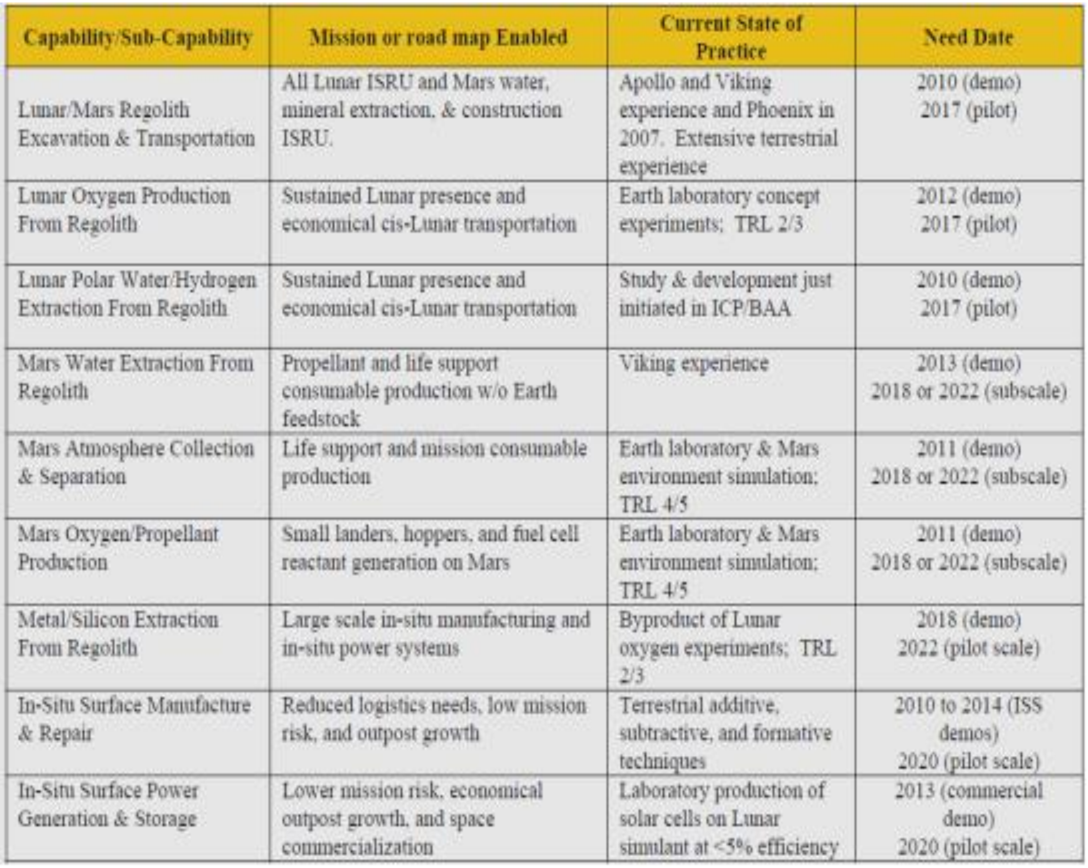
Risk assessment requires a context. Objectives may be broad (building a sustainable human settlement on Mars) or narrow (demonstrate an anchoring technology for attaching to a spinning asteroid). Likewise, risks cut across many categories (systems, technologies, operations, economic, regulatory, human health). Once the scope is defined, potential risks can be rated in terms of impact, likelihood, speed of onset and vulnerability [Curtis, 2012].

Risk assessments are already mandatory in many industries – compliance with US Government regulations such as anti-money laundering, Basel II, and Sarbanes-Oxley all require formal risk assessments that include monitoring client accounts, operational risk management, and controls over financial reporting. Risk assessment is the foundation of an effective Enterprise Risk Management program (see guidelines published by the Committee of Sponsoring Organizations or COSO) [Curtis, 2012].

5.6.2 Assessment of Key SMR Technologies

SMR technologies are currently immature and are critical to a whole new paradigm in space development costs. Advances in SMR systems readiness levels will significantly reduce risks for human space exploration and settlement. In general, technology development trades an R&D cost with more robust future systems performance. For example, the development of lunar surface manufacturing or a 3D metal printing capability could dramatically reduce the need for spare parts, increasing mission reliability and reducing long-term costs.

> *"The Key Capability table below for ISRU was compiled after a multi-step process. First past ISRU technology and mission studies and reports were examined to identify ISRU capabilities and quantify the benefits of these capabilities to extending or enabling individual missions and complete architectures. Then the identified capabilities were compared to each other to determine relative ranking. The capabilities/sub-capabilities listed in the table were those that were identified as supporting multiple ISRU capabilities (ex. Excavation and Surface Cryogenic Fluid Storage), that are applicable to both the Moon and Mars, or are critical for achieving significant mass, cost, and/or risk reduction benefits for individual missions or architectures as a whole. This list provides information on the missions enabled and the need date for this capability to be ready for incorporation into human missions"* [Sanders, 2005]



Capability/Sub-Capability	Mission or road map Enabled	Current State of Practice	Need Date
Lunar/Mars Regolith Excavation & Transportation	All Lunar ISRU and Mars water, mineral extraction, & construction ISRU.	Apollo and Viking experience and Phoenix in 2007. Extensive terrestrial experience	2010 (demo) 2017 (pilot)
Lunar Oxygen Production From Regolith	Sustained Lunar presence and economical cis-Lunar transportation	Earth laboratory concept experiments; TRL 2/3	2012 (demo) 2017 (pilot)
Lunar Polar Water/Hydrogen Extraction From Regolith	Sustained Lunar presence and economical cis-Lunar transportation	Study & development just initiated in ICP/BAA	2010 (demo) 2017 (pilot)
Mars Water Extraction From Regolith	Propellant and life support consumable production w/o Earth feedstock	Viking experience	2013 (demo) 2018 or 2022 (subscale)
Mars Atmosphere Collection & Separation	Life support and mission consumable production	Earth laboratory & Mars environment simulation; TRL 4/5	2011 (demo) 2018 or 2022 (subscale)
Mars Oxygen/Propellant Production	Small landers, hoppers, and fuel cell reactant generation on Mars	Earth laboratory & Mars environment simulation; TRL 4/5	2011 (demo) 2018 or 2022 (subscale)
Metal/Silicon Extraction From Regolith	Large scale in-situ manufacturing and in-situ power systems	Byproduct of Lunar oxygen experiments; TRL 2/3	2018 (demo) 2022 (pilot scale)
In-Situ Surface Manufacture & Repair	Reduced logistics needs, low mission risk, and outpost growth	Terrestrial additive, subtractive, and formative techniques	2010 to 2014 (ISS demos) 2020 (pilot scale)
In-Situ Surface Power Generation & Storage	Lower mission risk, economical outpost growth, and space commercialization	Laboratory production of solar cells on Lunar simulant at <5% efficiency	2013 (commercial demo) 2020 (pilot scale)

Figure 5-23 SMR Capability and Technology Needs [Sanders, 2005].

5.6.3 Leveraging 65 Years of Experience in Space

The phenomenal successes of recent space ventures, such as China's orbiting and landing on the Moon along with India's orbiting Mars, are based upon tremendously high risk & reward related activities called 'operating in space.' The early years were full of rocket failures and non-operating satellites, without much knowledge of why they failed. After years of study and experimentation, the space community now routinely goes with confidence where no one went before. The ability to operate in this hostile environment has developed mostly from careful leveraging of 65 years of failures that included mysterious satellite anomalies. Any advance into space to prospect, exploit, and mine minerals and other resources will similarly leverage the lessons learned by our predecessors. A few of the challenges involved include:

Emptiness

<u>Vacuum:</u> The pressure in space is near zero and would create a tremendous pressure differential against anything that wants to maintain Earth's normal pressure. This is especially true for humans; but it also is the case for sensitive equipment not designed to work in a vacuum. Tremendous care will be taken to ensure that human habitats are maintained at an acceptable pressure level. The transition from and to the vacuum environment is dramatic and requires careful planning.

<u>Cold – Hot:</u> As the emptiness of space will not maintain a temperature, the extremes potentially present during flight go from close to absolute zero to significantly hotter than humans can bear. As a result, the temperature changes can be well over 300 degrees centigrade when going from sunlight to dark shadows. Such a variation can also potentially occur when moving around the outside of a spacecraft as well as on the surface of the Moon or asteroids, and it occurs 28 times a day in Low Earth Orbit (LEO). When in flight beyond LEO, the thermal situation will depend upon the distance to the Sun and on the possibility of a spacecraft being in the shadow of a large body.

Solar Radiation

The sun generates a broad spectrum of electromagnetic radiation that includes ultraviolet rays, gamma rays and X-rays. As the Sun varies its activity over an 11-year cycle, certain significant solar events (flares) not only generate dangerous, enhanced, electromagnetic radiation, but they can also be associated with the acceleration of particles up to several hundred MeV/nucleon - in some instances up to a few GeV/nucleon. Of particular importance in this regard are those Solar Energetic Particle Events (SEPs) which are associated with the propagation of fast coronal mass ejections (CMEs) through the interplanetary environment while carrying, frozen into the ejected mass, the local solar surface magnetic field. In a transition region between the normal sectored magnetic field structure of interplanetary space and the fields frozen into the ejected material, a shock is formed within which constituents of the interplanetary plasma are accelerated to form an SEP which is mostly composed of protons with, in addition, about 10% Helium and <1% heavier elements. These particles can, in the case that they are accelerated to form, hard spectrum, highly energetic events, be hazardous to human space crews.

At the present time extreme SEPs cannot be predicted. However, statistical studies are in train to determine their likely-hood of occurrence over time. Meanwhile there have been many solar events that could have caused death to an unprotected human in a spacesuit.

Cosmic Rays:

Galactic Cosmic Radiation (GCR) consists, in the interplanetary medium, of atomic nuclei that have been ionized and accelerated to very high energies, probably by supernova related shocks. Their composition is of the order of 85% protons and 14% alpha particles, with the remainder comprising heavier nuclei in the general range from lithium to uranium. Nuclides up to and including iron can be important in producing biological damage. Although the energies of cosmic ray particles can reach 1020 MeV, most of the deleterious effects produced by this radiation are associated with nuclei in the energy range from several hundred MeV/nucleon to a few GeV/nucleon. A conservative value of 10 MeV/nuc is usually taken to define the threshold energy of particles potentially dangerous to humans in interplanetary space, where GCR constitutes an isotropic source of radiation. This radiation shows some solar cycle dependence due to the shielding provided from incoming galactic cosmic rays at, for instance, the Earth and Mars due to the presence in interplanetary space at solar maximum of complex solar related conditions.

Mitigation Measures

To reduce the risk of radiation damage to humans and electronics due to hard spectrum SEPs and GCR, the space community is currently developing many strategies that include:

- Designing onboard electronics to withstand intense radiation through hardening the components or placign a spacecraft in hibernation before a predicted solar radiation storm
- Shielding the crew as best as possible using available resources (e.g. within a bio-well), or through suitably re-orienting a

particular spacecraft when the arrival of damaging radiation is forecast.

Densities in Space:

Dust: We see space as being very empty; but it is hazardous to be hit by anything at the speeds inherent in space travel. Even small particles will erode the structure of space systems and impact fragile portions of spacecraft. The vacuum seems total, but it contains both particles and larger objects. In addition to microscopic dust particles, there are micrometeorites. The Earth increases its mass by 40,000 tons of dust each year. This gives the reader a feeling for the density of small particles around our planet.

Space Debris and Satellites: As we have been parking defunct satellites in orbit around the Earth since 1958, we have, in consequence, been making space travel a little more hazardous every year. The densities of space debris and satellites are still miniscule; however, the consequence of hitting anything going at 17,000 miles/hour is dramatic. The good news is that space debris from satellites is now continuously monitored and a predictive technology exists to assist in on-orbit collision avoidance.

Launch to Orbit: The capability to reach orbit safely has in recent years increased dramatically and has thereby lead to confidence in planning future missions. While the probability of a rocket explosion during launch has gone down, it is still an uncomfortable ride. The acceleration from zero to 17,000 mph is tremendous with associated shaking of the payload constituting a damaging process. Overall, launch to orbit is hazardous and difficult.

Crew Support: The difficulty of keeping a satellite operational and ensuring that its crew is kept safe is challenging. Not only is it necessary to provide the same protection that one would give to a robotic satellite but it is further required to: provide consumables [food, water, air, etc.]; accommodate waste disposal; ensure temperature range control; keep the pressure within the human comfort range, and discharge any hazardous gases built up inside the living quarters. In addition, there are the psychological issues accruing to humans who stay in isolation for extended periods of time with minimum human contact and constant awareness of the tremendous dangers only centimeters away.

The bottom line is that we have a tremendous history of successful operations in space AND we are continuously learning about the environment and the process of protecting equipment and people. These lessons will be essential to any commercial, or government, ventures beyond low Earth Orbit, with or without humans. The problems are immense, but the solutions are achievable and based upon 65 years of heritage.

5.6.4 Protection of the Earth

In the past, Lunar Landers have brought back material from the Moon. In addition, the Japanese returned samples from their rendezvous with asteroid Itokawa in mid-September 2005. Each of these programs was carefully managed to ensure that the Earth was protected from back - contamination. Indeed, as adventurers go after space mineral resources, they must ensure that the Earth is protected from pollution from outer space. There is presently an office in most of the national space agencies creating approaches to this threat. The SMR community must ensure that they participate in the planning and execution of the guidelines thereby developed.

5.7 Status of SMR Technology Development Programs

The cancellation of the Constellation program, which was developing capabilities for human lunar and Mars exploration, also reduced NASA's investment in SMR technology maturation. The heritage argument (if a space system has not been flown in the past, it does not belong in today's mission planning because it would introduce too much risk) has been used all too often to suppress the incorporation of SMR into NASA's mission and architecture planning. The Constellation program marked the beginning of a reversal in this philosophy. SMR technology development is being undertaken by public and private agents in the US, Canada and Europe, with a growing base of support. The potential for commercial applications and future profits adds incentive for private investment in technology maturation. Interest in lunar and asteroid resources is being publically announced by a growing number of private entities including Shackleton Energy Company, Planetary Resources, Deep Space Industries, Golden Spike and Moon Express. This clearly implies commercial interest in maturing SMR technology. Given the preponderance of half-mature technology at NASA, CSA and ESA (with many TRLs in the 3-5 range), this would create an incentive for partnerships or spin-out opportunities. The appearance of private agents could also introduce an element of secrecy or stealth regarding true TRL levels.

5.7.1 Identification of Key SMR Risks

Space settlement will introduce humans to new levels of risk and reward. SMR in general is a powerful risk mitigation strategy for settlement; yet, it will encounter its own unique set of inherent risks. Creating a framework for tracking and anticipating those risks is the goal of this section. Categories in the assessment process outlined below segregate primary risks into performance, economic technical and legal elements. Qualitative methods are a basic form of risk assessment, categorizing potential risks on nominal (categories only) or ordinal (ordered ranking) scales. Where data is available, more rigorous quantitative techniques (including benchmarking, probabilistic and non-probabilistic methods) can be used for assessing risk in a higher level of detail. Qualitative data enables more precise analyses of potential risk exposures (lower uncertainty), development of more relevant indicators, and rapid response to risk-enhancing events. A cornerstone of an effective corporate Enterprise Risk Management (ERM) process is the tracking and measurement of key risk indicators through iterative efforts and rigorous data collection. SMR risks can and should be tracked using ERM protocols as they evolve and more data becomes available, leveraging industry talent and the statistical tools used by actuaries. The next table will list many of the risks that should be considered during the development of a program.

Category	***Risk***	***Comments***
Performance	Leadership & Management	Inexperienced leadership and management is a significant source of program risk, resulting in cost overruns, delays and even cancellation.
	Interface	External interface complexity has added risk to large-scale US DoD programs
	Requirements Creep & Cost	Incomplete or unstable requirements increase schedule and cost risks.
	Complexity	Increased flexibility enabled by advances in computer hardware and software provide engineers and managers with far more design options
	Software	Increased flexibility enabled by advances in computer hardware and software provide engineers and managers with far more design options
Economics and	Finance	Drawing proper systems boundaries around the aggregated

Business		total risk associated could mitigate risks such as debt, equity and credit risk assessments.
	Cost	assess the stability of the business cost environment
	Market	market risk assessment would evaluate the likelihood of market movements that could adversely affect performance goals or that could increase risk exposure
	Price	Understanding price stability or variance is critical to predicting long-term enterprise
Technical	Launch	Space launch is a risky and technically complex activity that results in regular and statistically-predictable failure rates
	Component to spacecraft	Mission success depends on a low probability of spacecraft failure over the design life
	Operations	evaluate of the risk of loss resulting from inadequate internal processes, people or training relating to the operating environment of the enterprise
	Environmental	The risk of orbital debris impact is well understood and statistically measurable
	Resource	*"With respect to Resource Risks, there are three primary concerns: the resource of interest is not available at all, the resource of interest is not available at the landing site, and the resource of interest is at the landing site but not in the form, location (depth or areal concentration), or purity expected."* [Sanders,2005]
Legal and Regulatory	Regulatory Uncertainty	New financial markets tend to improve the efficiency of capital allocation as they mature and gain wisdom, yet often retain a core level of unpredictability
	International Taxation Uncertainty	Controlling revenue or tax uncertainty is a big issue to modern corporations.
	Regulatory Compliance	a compliance risk assessment will step beyond its typical limited use in comparing corporate practices with legal standards in finance and taxation

Table 5-4, Risk Breakout for SMR Ventures

5.7.2 Risk Mitigation Strategies

Mitigation is a common industrial response to risks, threats and challenges. Reduction of specific risk classes is often framed as an investment. Technology maturation is a well-understood process in aerospace (as well as other industries) that steadily reduces technical risk for a given investment cost. Exploration expenditures also reduce resource or geologic risk in the mining industry. Process safety improvements follow the same pattern, where operational changes can reduce risks but take time and training costs to implement. Primary risk abatement categories relating to SMR and human space settlement in this section include technical improvements (including maintenance & repair and space manufacturing), information gathering, systems engineering, legal & policy support, and public/private partnerships.

Technology Development is Risk Mitigation

Extensive effort has been put into minimizing architecture, spacecraft and mechanism risk starting at the component level by building up systems with the highest quality, most reliable building blocks and by using redundancy and other creative risk reduction methods. This strategy is based upon the assumption that reacquiring a target after it is launched is extremely difficult and costly, making maintenance and repair all but impossible. This assumption and strategy also drives a lot of current technology development in aerospace: A drive to find the maximum reliability combination of material, design and method for getting things done in space subject to the constraint of minimizing mass, power, cost and completion timeframe. The resultant lowered risk while expanding capability, yet is still limited by a system's cumulative risk distribution. In short, development of new technology is always a risk mitigation process.

Maintenance & Repair for Improved Reliability

Prior effort in minimizing spacecraft and mechanisms risk began with building up systems using the highest-reliability components available, no matter how costly. Reusability and maintenance offer sharp reductions in mission risk by offering a spacecraft with a different relationship within statistical mathematics that predict how cumulative risk is measured. This actually rewrites the copula equation that drives system reliability. The result reduces risk's statistical dependence by removing links in the middle of a spacecraft's Markov chain, making accessible risk values an order of magnitude or two lower than previously thought possible.

Planetary surface operations offer a significant departure from the historic "no-catch" assumption (especially operations from a human-tended base or settlement). This new approach depends upon a risk reduction argument based upon the assumption that maintenance and repair will have become proven technologies (a simpler assertion to defend when modeling future capabilities). In short, higher systems reliability and lower mission or operations risk than experienced in prior space missions is a reasonable assumption, providing a resupply node is available.

Reusability and Propellant Supply Reduce Transportation Risk

Reusability can similarly linearize the cost equation, decoupling it from the rocket equation, and will allow capital assets (spacecraft, habitats, mining equipment, etc.) to be more effectively employed in the future, dramatically lowering several classes of systems risk. All one needs to enable this assumption is a series of one or more nearby resupply / logistics nodes. The availability of refueling technology, local operations and routine maintenance will cause significant changes to the all-expendable paradigm, dramatically lowering costs. For costs beyond LEO, today's aerospace industry continues to operate on the tip of an exponential function - the rocket equation. Economic evaluation reveals a hidden assumption that it is "normal" to amortize a capital asset in one trip. The reusability/refuelability capability combines well with maintenance and repair functions to enable even sharper reductions in mission risk compared to the single-stack, all-expendable architecture. The terrestrial combination of maintenance and repair with refueling at service stations for automobiles is no accident.

Local Manufacturing Reduces Human Settlement Risk

Thanks to the current all-expendable paradigm, spacecraft production and launch costs are currently a function of distance – the farther you go, the more it costs – exponentially. The inverse of this – the ability to manufacture local finished goods (especially tools and repair parts) – is exponentially more valuable the farther the node is from the supply chain. An example of this would be a hypothetical 3D metal printing capability on the surface of Mars that could make parts or tools desperately needed by settlers, which would otherwise only be available on Earth with extreme costs and months of shipping delay between need and satisfaction. It is clear that local manufacturing is mission critical for human exploration, and is the only available option to reduce the various risks listed above to a range that is acceptable for human settlement.

The Role of Science and Information in Risk Reduction

Science is a "gather more data" approach to risk reduction. Not enough information leads to uncertainty which leads to greater risk. Current uncertainty regarding asteroid composition (particularly the valuable trace elements) and mechanical properties can be used as an excuse for nonparticipation. This idea persists despite the robust and random sample return program the asteroids have been doing on Earth for millennia (meteorite collection is rich and diverse, just not directly correlated with parent bodies). Solution: Robotic spacecraft missions are needed to establish “ground truth” for SMR.

Engineering Demonstrations
Incremental reduction of systems risk can also be accomplished by engineering demonstrations. Indeed, combining science and engineering demonstrations into the same spacecraft offers a powerful risk reduction strategy that could accelerate commercial interest in SMR.

5.7.3 Systems Engineering Tools for Risk Assessment and Mitigation

Systems engineering and integration (SE&I) offers a robust set of tools for risk measurement and management. Originally developed to coordinate schedules, minimize systemic risks and manage resource flows for large complex projects, the SE&I process has developed into an indispensable tool for project management of all project phases from concept to retirement. Extensive industry experience exists in performance-based systems risk minimization [Kaminski, 2008]. Interface complexity risk is best addressed in the concept definition and architectural design phase by simplifying and standardizing user access points. Mitigation of inexperienced leadership problems can be offset by retention of key talent as well as robust training. Minimization of requirements creep is a function of clear vision and experienced leadership, combined with identification and negotiation of design tradeoffs as early in the process as is feasible. Clarity in partnership and collaboration roles between the users/sponsors and the developer are also critical to stabilize requirements in the formative phase of a program. Complexity risk can be minimized by partitioning a problem into separable pieces with simple interfaces, enabling incremental development and testing. This has the added benefit of enabling schedule acceleration by identifying opportunities for parallel subsystems development. Mitigation of software risk can be done by clearly defining functional allocations as early in the program as feasible. Mitigation of technological risk can be done by heritage-based baseline design, with pursuit of accelerating technology as a parallel activity with clearly defined crossover decision points based upon demonstrated maturity. Provisions in the architecture and systems design for technology insertions can add flexibility while minimizing requirements instability.

5.7.4 The Role of Public/Private Cooperation in SMR Risk Reduction

Cooperative public/private action can provide a powerful method of risk reduction, one with a long history and track record of success. Balancing short-term and long-term risk mitigation investments across the objective functions of both public and private stakeholders can leverage the best attributes of complementary systems of governance, each of which has relative advantages and disadvantages. Coordination and balancing of joint actions and goals is a function of both public policy and private strategic alignments.

How Private Agents Can Facilitate Public Objectives

Private agents can rapidly allocate capital for emerging opportunities, with low transaction costs due to naturally streamlined oversight and management. Permission to take risks often rests with a single point of authority (the investor or capitalist) or very lean management chains empowered by trust (contract by handshake), and not constrained by public accountability rules and red tape. These features can enable rapid expansion of private agents into new markets, technology arenas or areas of social change (e.g. media) which offer significant reductions in systemic risk (e.g. identifying suspects through data mining) as well as new capabilities for certain public functions. Business routinely invests in various classes of risk reduction, where little government intervention or budget is required. Where these investments provide a crossover public function, is a potential for net savings available to the taxpayer for public/private partnerships (PPPs).

The clever use of partnerships could benefit SMR and space settlement activities by reducing specific classes of both public and private risk. For example, at the government or space agency level, program cancellation risk dominates the risk equation (it is important to properly draw system boundaries – true risks are easily revealed this way). This has been a persistent problem with NASA's large-scale programs including human lunar and Mars exploration systems. Mitigating that risk would require holding elected officials accountable for the consequences of cancellation – something that a partnership could facilitate, particularly if significant private capital were put at risk. This same approach has successfully defended smaller programs in the past, and may now be in the beginning stages with some recent private human Mars exploration mission concepts, which are beginning to explore the potential for partnerships with NASA and large contractors.

Private Technology Maturation

The Bigelow Aerospace inflatable habitat module is an excellent example of how a private entity negotiated the purchase, in 2001, of an unfinished NASA technology and completed it, certifying a new emergent product or capability for use in space. TransHab technology was originally purchased from NASA by Robert Bigelow, who then used his own private funds to raise the TRL from 5 to 9, and provided the taxpayer a no-cost route to a dramatic reduction in mission risk for use of inflatable technology. Indeed, Bigelow may soon launch an inflatable module for use on the International Space Station. Note that finishing and space qualifying the technology was done *entirely off of NASAs books* at a significant net savings to the taxpayer. Bigelow Aerospace's purchase of TransHab-related patents ensures the company a long-term future in near-Earth space habitation systems sales. This may become a trend, one that provides an excellent example of Public/Private Partnership in action.

Incentives for Meeting Public Sector Needs

Compiling a generic list of incentives for private entities that could be awarded by governments for facilitating public sector needs or goals is an important step toward crafting win-win scenarios. This kind of list could enable policy to be crafted that maximizes benefits for both parties, identifying and quantifying the economic value or savings associated with PPP synergies. Examples of government-sourced awards or incentives include property rights, purchase agreements, indemnification and financial aids as expanded below.

How Public Agents Can Accelerate Private Enterprise

Cooperative public/private actions offer significant risk reduction opportunities for SMR. Examining the role of public agents in the nurturing, facilitation and expansion of private capabilities reveals that government can exert a strong influence on commercial viability of a new or existing player. This is a system that is also easy to exploit, explaining the rise in accountability rules and competitive bidding processes.

At the commercial enterprise level, market risk is often high with new technology. Early-stage users can play a critical role in the establishment of not only a customer base, but also production and operations experience, and even more critically - convergence on true cost and revenue functions. Government agencies can play a crucial role as an early adopter, particularly for systems with longer-term value, enabling firms to rapidly mature products and collect reliability data for larger, more mainstream commercial markets that follow. Market risk is likely to be a significant factor for SMR. Without a guaranteed paying customer, commercial funds invested in harvesting and refining SMR run a risk of financial loss. As an anchor tenant for space propellant supply, a government-sponsored human Mars expedition (for example) could guarantee a minimum SMR market size and price, paving the way for later customers. Other risks that could be reduced through agency or policy support include legal risk, financing risk and infrastructure-related risks. These will be discussed in more detail below.

Public policies mitigating commercial risks include revenue or market support (block purchases / anchor tenancy / concessions / tax breaks), credit enhancements (e.g., govt. guarantee bonds), provision of insurance (govt. backed or supported pool), direct government, or institutional investment, and indirect government support (nonfinancial interventions). Additional public policy supports are possible. Anchor tenancy or block purchases can mitigate market risks through contract law. Indemnity agreements and reinsurance can provide added tools for transferring risks between public and private constructs. Mitigation of transfer pricing issues related to uncertainty in international tax regimes is largely done today by using advanced pricing agreements (APAs) [Ernst & Young, 2012]. Similar agreements could be used by lunar or asteroid miners with governing entities or other parties having an interest to pre-negotiate tax and regulatory issues. Bilateral or multilateral tax agreements are also used to minimize transfer price risks; and, they could serve as a model for space commerce among multinational parties, again minimizing risk. Special agreements such as the Isle of Man's so-called zero-g zero-tax legislation is likely to draw businesses to themselves or others enacting similar laws. Finally, a simple no-cost policy could strongly enable SMR development, minimizing the type of legal risk and uncertainty the mining industry fears most when investing in former communist countries – the emergence of an internationally-recognized space property rights regime. Remember that the US transcontinental railroads were incentivized by giving railroad companies property rights along the right of ways. The economic value of property rights has been well documented.

SMR risks could be reduced by enabling subsets of today's rich international governmental spectrum to play an active, dynamic role in frontier enablement and support, significantly reducing operations and infrastructure risks by provision of emergent capabilities best suited for a public entity. Relevant terrestrial experience in government logistics support and resource management can be found by examining the roles of the Coast Guard and Army Corps of Engineers.

New government programs have emerged that are designed to explore PPP opportunities, leveraging joint resources where they provide value to public and private stakeholders. Examples of this include Government programs such as NASA's Commercial Orbital Transportation Systems (COTS) program, the NRO's Directors Innovation Initiative (DII), The Department of Commerce's Advanced Technology Program (ATP), and the commercialization team at the US Department of Energy's Energy Efficiency and Renewable Energy (EERE) program. These are some examples of the government side of successful PPP interfaces that are intended to expand opportunities and create hybrid or crossover solutions to risk reduction and capability expansion.

Tools for Mapping Win-Win PPPs

The principle of synergy - the interaction of multiple elements of a system to produce a net result greater than the sum of their individual effects - is the primary rationale for PPPs. Variables that could be useful in predicting win-wins for public-private partnership scenarios include integrated capability cost, systems-level costs, risk-adjusted costs (for offsets and/or reinsurance), net savings (enterprise vs. taxpayer or both), leverage ratios, and systems-level energy or materials inputs/outputs. Building a quantitative economic modeling framework that solves for net PPP value is a straightforward but tedious process. Benefits or rewards that have little or no marginal cost for one party (such as public property rights or private data byproducts) offer a point of departure for a PPP baseline.

To summarize, what Private agents can offer includes:

- Lower transaction costs and management overhead
- Rapid decision making without red tape or the need to extensively document permission
- Rapid access to capital / much faster budget cycles
- Faster, more flexible, more creative and better funded short-term product design
- Rapid market feedback

What Public agents can offer includes:

- Able to assign or defend property rights / intangibles
- Protection, market support, financing, insurance / indemnity at the enterprise or project level
- Long-term research and development (including fundamental science and engineering)
- Large-scale or long-term infrastructure projects
- Advanced exploration frontier bases

Economic and decision modeling frameworks and tools offer an excellent way to begin examining the PPP trade space. Optimization begins by identifying an objective function – for example, maximize PPP benefits, subject to constraints (risk, cost, budget, energy, schedule and/or intangibles). It is important to clearly define preferences (objectives) for outcomes and tolerance levels (constraints) that limit the systems of interest. Mapping risk preference or appetite is a critical input for this process.

An Example SMR Win-Win PPP

The potential for synergy, including risk reduction and cost savings between Asteroid mining and planetary impact defense is strong. It provides a good example of a PPP that could accelerate SMR by bringing the best of private enterprise and government together to solve one of the most dangerous and lucrative problems faced by modern society. The opportunity is due to four primary factors: A large relative amount of crossover between data needs (spectral, geochemical and geomechanical); high degree of common technology (including transport/anchoring and scientific instruments); interest in similar or identical targets (Earth-crossers are by definition closest to market); and, cross-training. A growing number of activities or publications of companies and agencies working in the field of NEAs are covering both mining and global defense-related topics.

Economic modeling tools offer a way to not only measure and predict risk reduction associated with an asteroid PPP model; but, it may also offer an ability to assess or measure the effect of a change in key assumptions or the quantitative advantage of a new technology or capability. The benefits of investment in technology improvements can be directly measured in an economic model, as long as their technical influence on results are predictable (for example, modeling a switch from chemical to nuclear propulsion in a mathematically precise way) and the model is set up to track those results within a specific context. Crafting international PPP decision criteria or guidelines can benefit from a framework that has quantitative measures of progress. Developing a framework that could model an optimal public-private partnership for asteroid development and defense could start with the following steps:

- Define goals and create an objective function from them.
- Map incentives for stakeholders as quantitatively as possible.
- Link goals to incentives using mathematical modeling.
- Define and quantify system constraints and limits.
- Create a self-correcting policy mechanism with data inputs and an iterative feedback loop to maximize goals subject to minimum systems cost while staying within constraints.

5.8 The Role of Risk in Opportunity Management

Risks are often opportunities in disguise. The ability to discern the difference between perceived and actual risk can make the difference between prematurity and early adoption of a critical breakthrough.

> *"An effective risk assessment yields forward-looking insight, not only allowing organizations to avoid risks, but providing greater and more meaningful clarity around the risks they do face. Armed with this insight and perspective, organizations are much better*

> *positioned to take the right risks, and can better manage them when they do. In the long run, organizations that continuously reposition themselves to capitalize on both quick wins and longer-term opportunities are more likely to meet—and surpass—their business objectives. It is this capability that will lead to measurable, lasting success in today's ever changing business environment."* [Atkinson, 2008]

Risk perception can also serve as a barrier to entry. Public vs. private risk preferences differ substantially; and, they can result from management feedback loops inherent in the governance environment. Risk seekers exist in public and private decision environments – each has important advantages and disadvantages. Portfolio theory says you should always bet a little money on high risk projects. True Mars risk preferences are being revealed.

5.8.1 Risk as a Barrier to Entry

True or even perceived risk can serve as a barrier to entry, inhibiting early competition thus protecting new markets from rapid early price reductions. Thus risk can cause a focusing effect, requiring competition to have more discipline or mettle in order to rise past the bar. This has the benefit of protecting larger profits for courageous investors. However, the inverse effect can also happen.

5.8.2 Public v. Private Risk Preferences

Risk appetite for public vs. private agents can be substantially different. Much of this is inherently environmental and can depend upon governance, feedback and reward systems. Assessment of risk preferences and tolerances can yield rich insights into the boundaries and limits within which an organization can effectively work – creating a process for anticipating responses to future events.

> *"Risk tolerance considers the relative importance of objectives and aligns with risk appetite. Risk appetite must be clearly defined and reflected in risk tolerances and risk limits to help ensure that organizational objectives can be achieved. From this information, a "risk/reward" measure can be derived to understand how levels of volatility affect operating income. This measure helps the organization pinpoint relative risk in earnings potential and target dependencies within lines of business."* [Atkinson, 2008]

Paying careful attention to the results of a company's risk assessment can set a foundation for establishing an effective Enterprise Risk Management (ERM) program, positioning a firm to capitalize on new opportunities as they arise as well as respond to emerging threats. Similarly, risk takers within government can face positive or negative feedback for breakthroughs. They often irritate fellow managers by forcing them to change and adapt while also developing allies and followers.

5.8.3 Development of Leading Indicators

"Leading Indicators" or risk-centric figures-of-merit can be helpful in anticipating problems and opportunities before they materialize. The development of technical figures-of-merit alone for SMR is insufficient if a true understanding of systems boundaries is desired. Leading indicators for systemic risks can provide critical insight into potential as well as perceived risks. Risk reporting is most meaningful when it tracks not only past events, but also offers forward-looking predictive analysis.

SMR Leading Indicators

Meaningful leading indicators can be used to contextualize sudden or gradual changes in key environments (governance, legal, physical, financial), identifying the potential for rapid growth, changing technology, or the likely emergence of new competitors or strategic alignment opportunities. Changes in both government and corporate environments are relevant to the development of SMR leading indicators, the best of which can anticipate the activation of key systems levers or tipping/activation points. A list of SMR and space settlement leading indicators would start with:

- Government (e.g. US Congress) willingness to support innovative PPPs (e.g. Dennis Tito's Inspiration Mars project)
- Aerospace industry becomes willing to explore financing options beyond government contracts, such as using debt or equity instruments to finance new capabilities
- Private SMR technology maturation rate increases, including spinoff adoption rate

- The total number of innovative PPPs accelerates through time, especially for small businesses which could benefit from commercializing new technologies (e.g. SBIR Ph3)
- The emergence of key supply line logistics nodes or capabilities (e.g. expanding capacity in the Deep Space Network for communications, propellant depots, etc.)

Risk indicator variables will also exert strong influence on SMR technical and economic readiness as they are so interrelated. Building on quantitative industrial assessment data, the benchmarking process is a source of high quality information analogs for a preliminary forward model anticipating SMR, settlement and manufacturing risks that can then be matured and modified as systems evolve.

> *"Historically, management has tracked key performance indicators (KPIs) to help detect issues affecting the achievement of objectives. In recent years, organizations have also been developing key risk indicators (KRIs) to help signal an increased risk of future losses or an uptick in risk events. KPIs and KRIs are tactical in nature, can be collected at any time, reported on a regular basis or as requested by management (e.g., as part of a balanced scorecard), and typically include statistics and/or metrics (often financial) that provide insight into an organization's risk position. Capturing KPIs and KRIs on management dashboards remains necessary, but it is also important for organization leaders to prompt broader consideration of market issues that could potentially create risk to the organization."* [Atkinson, 2008]

5.8.4 Opportunities can be Disguised as Risks

The difference between perceived and actual risk can be substantial, often disguising or obfuscating significant opportunity. Consider the example above of risk perception for a single Mars mission in either an expanding human Mars settlement vs. a small series of government Mars exploration missions. Many other examples exist – the entrepreneurs of Silicon Valley have experience with this phenomenon. Another way to say this is that the value of information can be very high at times.

The true value basis for SMR lies in today's wide and diverse array of industrial technology – very little of which is currently within the aerospace stovepipe. Significant future value will be generated from planetary surface and orbital construction using SMR as a source of feedstock. The first enterprises to gain industrial operations experience in the new physics will reap significant rewards from proprietary experience and the generation of new intellectual property. Risk perception is likely to serve as a barrier to entry, amplifying rewards for the first to market.

Technology Incompletion

Low-hanging technical fruit is available to private enterprise for the picking. A wide variety of high-TRL technologies exist that were started by NASA and taken to a level of process or bench-scale demonstration then abandoned. A growing number of these “orphaned technologies” reside inside the agency, as well as a wide network of small enterprises supported by government R&D funds such as the NASA Small Business Innovative Research or SBIR program. The need to prioritize and focus on mission-relevant needs is the primary rationale driving this incompletion process, which includes a wide variety of technologies related to SMR, spacecraft reusability, space manufacturing and repair. Agency insistence on maximizing heritage and base lining expendable systems reinforce this bias. Heritage can be a valuable design principle for minimizing risk under steady-state conditions. However, conditions today are far from steady-state, introducing distortions (the principle may indeed be tying parts of the US defense industry to old technology). It is also important to remember that Apollo had extremely low levels of heritage.

Fear about radical changes in program management and cost predictability that would be engendered by game-changing SMR capabilities may also contribute to the inhibition of systems adoption by government. In short, incompletion in publically-funded SMR and space settlement technology may be partly due to structural reasons, yet the positive opportunity created for new-space commercial enterprises more than offsets this negative, creating a net positive balance or latent potential energy in the larger system. This fact could serve to ignite afterburners once private SMR begins to take hold by radically shortening the path between good idea and space capability. Bigelow Aerospace provided an excellent example of this when they purchased, privatized and completed TransHab, raising inflatable space module technology to TRL9 with their own money. It is surprising that to date no one has picked up the Mars In-Situ Sample Return (MISR) flight hardware for a private flight demo of SMR on Mars; or, other surfaces. TRL8 flight ready hardware already exists and has been sitting on a shelf at NASA-JSC for over fifteen years – a ready-made CO2 to O2 / Methane conversion demonstrator built for a Mars lander.

5.9 Technology Readiness and Risk Assessment Summary

Summarizing the influence of SMR-related technologies and risks on space exploration and development is quite simple. The primary rationale for SMR technology investment is to buy-down space exploration and settlement risk. Significant risk reductions are available if statistical Markov chains can be cut and segmented into much shorter links – an option that only SMR can provide. System dependence on high-reliability, redundant design has favored heritage as a design strategy in the past. Today SMR offers a completely different, and much richer, palate of colors from which to paint our collective future. In addition, technologies that are needed to accelerate space development could also "save the Earth" from planetary destruction by asteroid impact.

Part C – Illustration of the Concepts by Explaining Current or Future Design Reference Missions

5.10 SMR Design Reference Missions

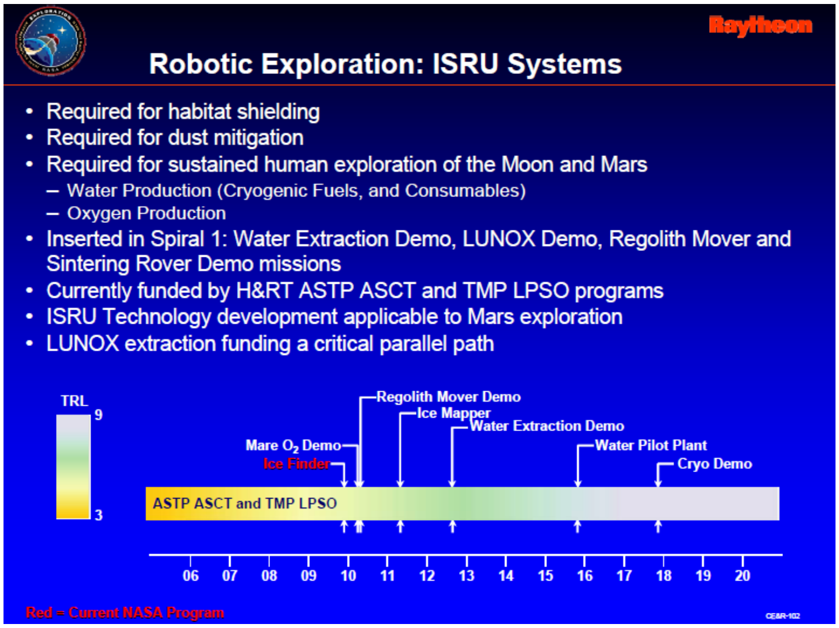
Aerospace "Design Reference Missions" (DRMs) establish the methodologies of potential space missions, so that discussions about them use the same assumptions for how they would be accomplished. Missions to the Moon, for example, can assume one giant rocket like the Saturn 5 used in the U.S. Apollo program; or, they could be based upon multiple launches of smaller payloads that are assembled in Earth orbit, lunar orbit, or another location. Each variation would be a Design Reference Mission with uniform assumptions about the methods involved and the goals driving design choices. For the Apollo program, for example, the overriding goal was delivering a crew to the lunar surface sooner than the Soviet Union. Other goals, such as reusability or cost, played much smaller roles. For SMR, the Design Reference Mission

(DRM) summarizes both the methods to be used and the primary goals to be achieved.

NASA has extensively studied the potential use of lunar resources to reduce the cost of human lunar missions – this process has been ongoing for over 50 years. The primary argument for the utility of SMR can be summed up as follows:

> *"Numerous studies have shown that making propellants in-situ can significantly reduce mission mass and cost, and also enable new mission capabilities, such as permanent manned presence and surface hoppers. Experience with the Mir and International Space Station and the recent grounding of the Space Shuttle fleet have also highlighted the need for backup caches or independent life support consumable production capabilities, and a different paradigm for repair of failed hardware from the traditional replacement approach of orbital replacement unit (ORU) spares for future long duration missions. Lastly, for future astronauts to safely stay on the Moon or Mars for extended periods of time, surface construction and utility/infrastructure growth capabilities for items such as radiation protection, power generation, habitable volume, and surface mobility will be required or the cost and risk of these missions may be prohibitive."* [Sanders, 2005]

Over the last 40 years since Apollo, the government has developed DRMs for placing people on bodies inside our solar system. All have been designed for international governmental joint missions, with some leveraging SMRs. Most of these only use in-situ resources in their models while some talk of transporting fuel and water. This study is focused upon commercial ventures when SMRs are leveraged to achieve missions – governmental and commercial. The list is long for DRMs, and most are very similar in their resulting plan. NASA has extensive information on DSMs centered on each of its national level approved programs, such as Constellation. As a result, this study will look at one of the last DRMs that has relevance – government mission to an asteroid. The pictures below show historical looks at our problem. They are from a Raytheon study and Lockheed Martin archives. The topic is in-situ resources.

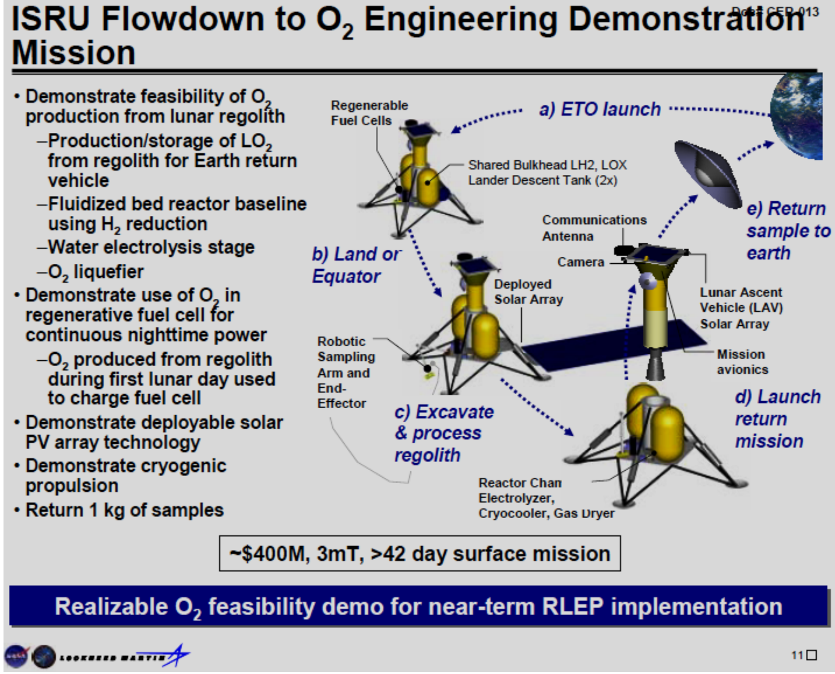


Robotic Exploration: ISRU Systems

- Required for habitat shielding
- Required for dust mitigation
- Required for sustained human exploration of the Moon and Mars
  - Water Production (Cryogenic Fuels, and Consumables)
  - Oxygen Production
- Inserted in Spiral 1: Water Extraction Demo, LUNOX Demo, Regolith Mover and Sintering Rover Demo missions
- Currently funded by H&RT ASTP ASCT and TMP LPSO programs
- ISRU Technology development applicable to Mars exploration
- LUNOX extraction funding a critical parallel path

Red = Current NASA Program

Figure 5-24, Lunar Architecture with SMR roles [Raytheon, 2005].



ISRU Flowdown to O_2 Engineering Demonstration Mission

- Demonstrate feasibility of O_2 production from lunar regolith
  - Production/storage of LO_2 from regolith for Earth return vehicle
  - Fluidized bed reactor baseline using H_2 reduction
  - Water electrolysis stage
  - O_2 liquefier
- Demonstrate use of O_2 in regenerative fuel cell for continuous nighttime power
  - O_2 produced from regolith during first lunar day used to charge fuel cell
- Demonstrate deployable solar PV array technology
- Demonstrate cryogenic propulsion
- Return 1 kg of samples

~$400M, 3mT, >42 day surface mission

Realizable O_2 feasibility demo for near-term RLEP implementation

Figure 5-25, SMR Precursor Missions [Lockheed Martin, 2005].

5.10.1 NASA Human Asteroid Mission DRMs

The 2010 cancellation of Project Constellation, and announcement of a replacement human asteroid mission in 2011, underscores the fragility of long-term, high-cost, human space initiatives based solely upon a single government agency's budget under the direction of a chief executive who changes more frequently than the project could be completed. Discussion of "programmatic risk" and mitigation strategies basically boils down to creating international and commercial partnerships.

> *"As had been rumored for days, Obama's blueprint for NASA would cancel the Constellation program, the family of rockets and hardware now in development to replace the aging space shuttle, and would call instead on commercial vendors to fly astronauts to orbit."* [Matson, 2010]

President Barack Obama outlined a new human mission destination during a visit to the Kennedy Space Center in 2010.

> *"By 2025, we expect new spacecraft designed for long journeys to allow us to begin the first-ever crewed missions beyond the moon into deep space," he said. "We'll start by sending astronauts to an asteroid for the first time in history."* [Borenstein, 2010]

Some experts considered implementation of this initiative more difficult than a human lunar mission. Timelines offering access to asteroids are infrequent, and minimum energy trajectories can take years, making a human mission more difficult to plan. Add to this the need to keep a very tight timeline – there is only one launch opportunity per asteroid, compared with weekly opportunities for the Moon and bi-annual for Mars.

> *"The Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) began in September 2010 under the auspices of NASA Headquarters Planetary Science Division of the Science Mission Directorate in cooperation with the Advanced Exploration Systems Division of the Human Exploration and Operations Mission Directorate. Its purpose was to identify any known NEOs, particularly Near-Earth Asteroids (NEAs) that might be accessible by future human space flight missions."* [JPL, 2013]

The NHATS study identified "several dozen targets" for human asteroid missions.

> *"NEAs are among the most exciting and intriguing destinations in our solar system for human explorers. While there are only eight planets, there are many thousands of NEAs, each a fascinating and unique world unto itself whose secrets contain the clues to our*

> *primordial past and the keys to our future aspirations. We are therefore quite fortunate that round-trip missions to any of the 1,071 currently known NHATS-compliant NEAs require less delta-v than round-trip missions to Mars, and round-trip missions to hundreds of those NEAs require less delta-v than a round-trip mission to the lunar surface. There are even several dozen of those NEAs for which round-trip missions require less delta-v than a round-trip mission to lunar orbit or an Earth-Moon Lagrangian point orbit, and we discover more NEAs on a continual basis."* [Barbee, 2013]

However, the "good rendezvous targets" lined up later in the 2020's, past NASA's anticipated return of human exploration capability beyond LEO. One solution would be to deploy cameras to identify smaller targets that are likely to exist; but, are too small to see with current assets.

> *"The data … show that the currently known NEA population is lacking in sizable members with accurately determined orbits offering low delta-v, short duration mission opportunities during the early to mid-2020s. This has led the technical community concerned with NEOs to recommend the deployment of a space-based NEO survey telescope that would avoid the geometrical constraints associated with observing solely from Earth and thus provide a very comprehensive NEO population survey within only a few years of deployment"* [Barbee, 2013]

Another option for a human asteroid mission was identified by the Keck foundation in April of 2012 [Keck, 2012]. This breakthrough study has come to define **NASA's current vision of a human space exploration mission**: Capture and return a small asteroid (or piece of a larger one), park it at EML-1 and lunar orbit, then send astronauts to investigate (see image below for more detail).

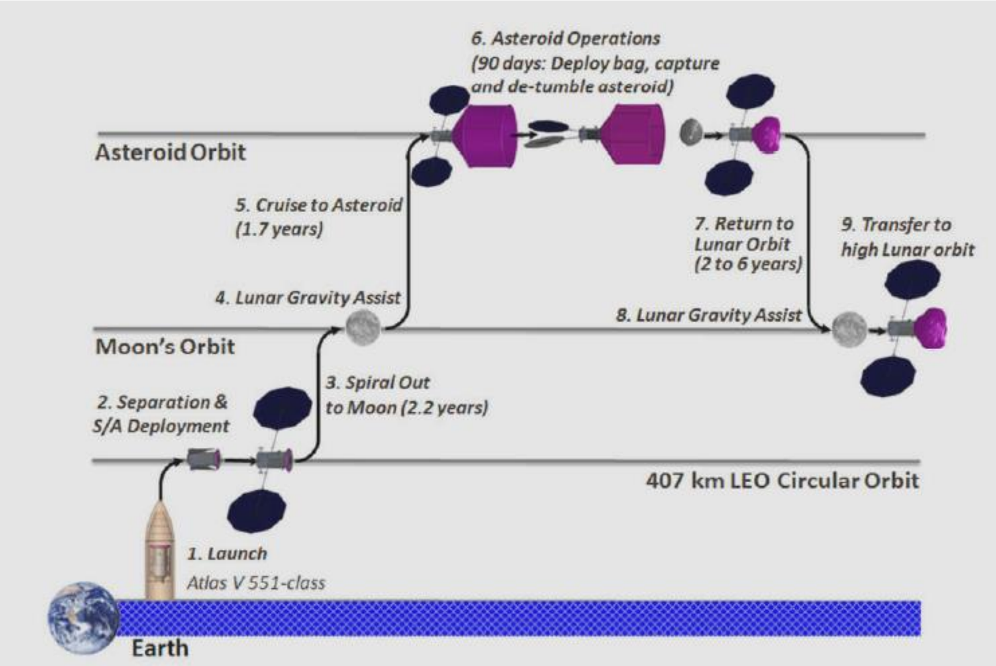


Figure 5-26, Bat Chart Asteroid Return Mission [Keck, 2012].

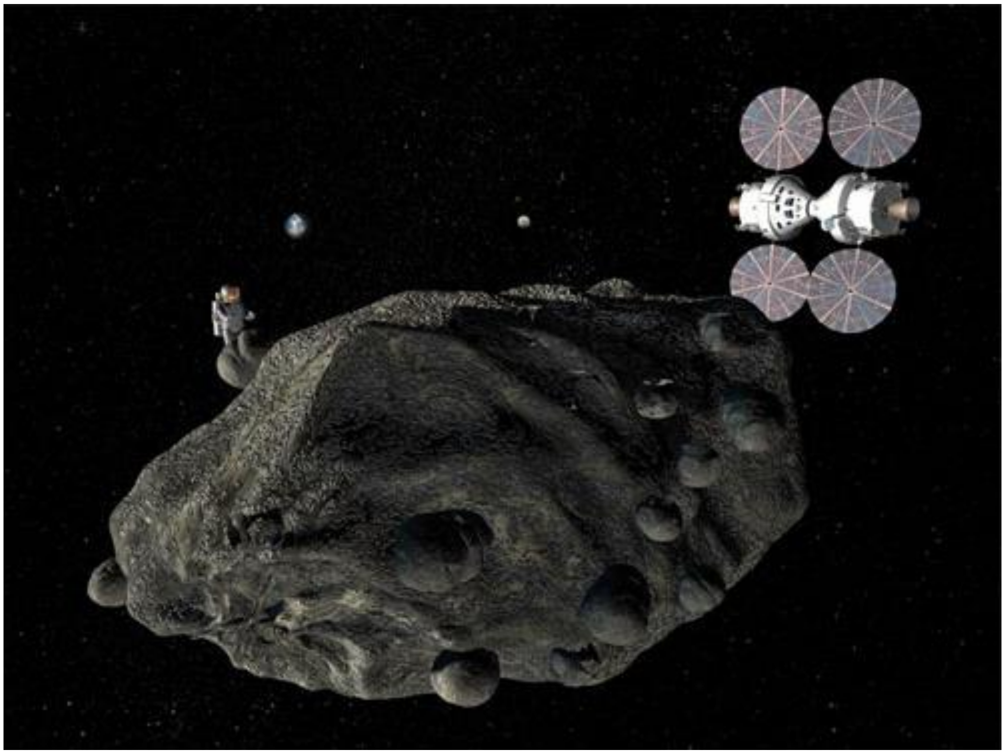
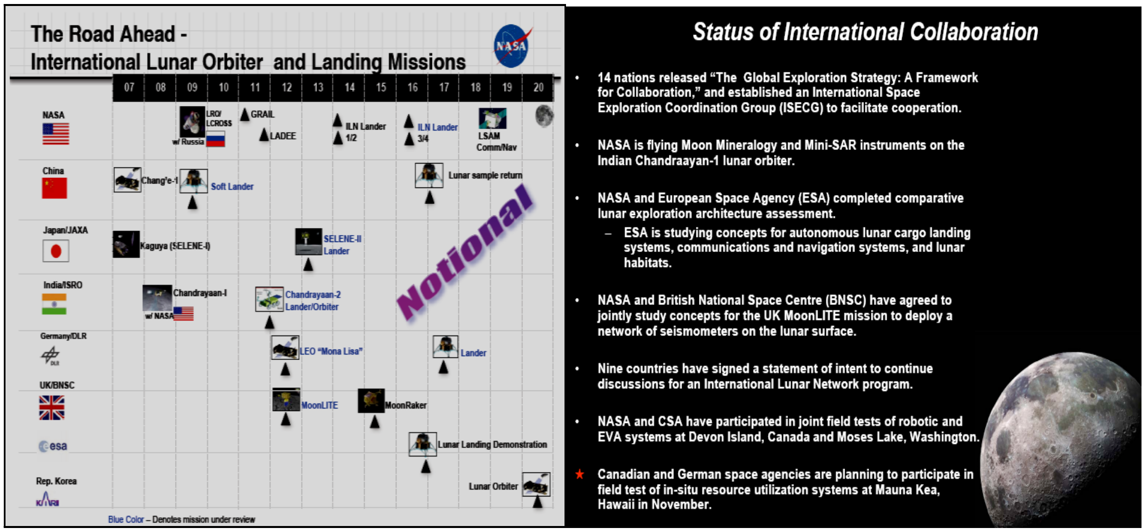


Figure 5-27, Visualizing Human Visit to an Asteroid [NASA, 2012].

5.10.2 International Governmental Design Reference Missions

In November 2007, a mechanism was set up in order to facilitate dialogue between international government parties regarding future lunar exploration and development with the establishment of the International Space Exploration Coordination Group (ISECG) [Yoder, 2008].

> *"Over the last 6 months, representatives from NASA and the European Space Agency, or ESA, have been engaged in a detailed assessment of potential programs and technologies that when conducted cooperatively could one day support a human outpost on the moon." … "The study assessed the degree to which NASA and ESA's lunar exploration architecture concepts could complement, augment, or enhance the exploration plans of one another. Technical teams from each agency engaged in a series of joint, qualitative assessments of the potential scientific and exploration benefits from collaboration between the ESA capabilities under study and NASA's space transportation systems and lunar surface exploration architecture concepts."* [Braukus, 2008]



The Road Ahead - International Lunar Orbiter and Landing Missions

Status of International Collaboration

- 14 nations released "The Global Exploration Strategy: A Framework for Collaboration," and established an International Space Exploration Coordination Group (ISECG) to facilitate cooperation.
- NASA is flying Moon Mineralogy and Mini-SAR instruments on the Indian Chandraayan-1 lunar orbiter.
- NASA and European Space Agency (ESA) completed comparative lunar exploration architecture assessment.
  - ESA is studying concepts for autonomous lunar cargo landing systems, communications and navigation systems, and lunar habitats.
- NASA and British National Space Centre (BNSC) have agreed to jointly study concepts for the UK MoonLITE mission to deploy a network of seismometers on the lunar surface.
- Nine countries have signed a statement of intent to continue discussions for an International Lunar Network program.
- NASA and CSA have participated in joint field tests of robotic and EVA systems at Devon Island, Canada and Moses Lake, Washington.

★ Canadian and German space agencies are planning to participate in field test of in-situ resource utilization systems at Mauna Kea, Hawaii in November.

Figure 5-28, International Lunar Exploration [Moore, 2008].

Dialogue among international space agencies lead to joint trade studies wherein the Japanese Space Agency (JAXA) and European Space Agency (ESA) examined opportunities for participation that leverage their core capabilities.

> *"In this evolving international context, ESA has intensified its reflections on its space exploration roadmap elaborated during the preparatory phase of the Programme and long-term exploration scenarios as well as on the different elements and capabilities on which Europe should put emphasis to identify candidate missions*

> *for the future and ensure a meaningful and robust contribution to the global undertaking."* [Hovland, 2005]

Indeed, this evolving series of dialogues stimulated dialogue and planning for the human space exploration and SMR, as illustrated by the quote and figure below:

> *"ESA has developed a long-term, international space exploration roadmap, based on a current understanding of international space exploration plans. The roadmap assumes development of exploration architectures in a phased approach, leading ultimately to the implementation of the first international human mission to Mars. The phased approach allows for the incremental development of technologies and systems over time, and is mindful of both political constraints and financial budgets. The four phases are:*
>
> - *Phase 1, through 2016 and perhaps through 2020: This period will see the advancement of human operations in LEO based on extensive utilization of the International Space Station (ISS), or potential new orbital infrastructures. At the same time, the development of a new generation of crew space transportation systems, designed for access to both LEO and low lunar orbit (LLO), will secure human access and frequent flight opportunities to space. Early robotic preparatory missions towards the Moon (e.g. the International Lunar Network) and Mars will pave the way for future human exploration and demonstrate key capabilities such as planetary descent and landing, surface mobility, in-situ resource utilization (ISRU), and perform valuable in-situ science.*
> - *Phase 2, early-to-mid 2020s: This period could see extended human operations in LEO based on the transition to new orbital infrastructures replacing ISS, while first human missions to the Moon commence. During this period, further orbital infrastructures beyond LEO (e.g. in LLO or at the Earth-Moon libration points) might be constructed as an element of a transportation architecture. Such infrastructure could facilitate the assembly of vehicles, crew exchange, docking operations, lunar landings and sustained surface operations, while also enabling research for interplanetary mission preparation. The first Mars Sample Return mission would be implemented during this phase and its findings will drive further Mars exploration.*

- *Phase 3, late 2020's or early 2030s: Phase 3 would introduce extended lunar surface installations for fixed and mobile habitation and research. ESA assumes that during this phase lunar exploration would move forward as a coordinated international endeavor. Initial activities towards the preparation of an international human mission to Mars may commence.*
- *Phase 4, mid-to-late 2030s: Based on the essential knowledge gained from and capabilities developed for continued lunar surface activities, Phase 4 will see the implementation of the first human Mission to Mars. Continuation of lunar surface activities will depend on the long-term exploitation objectives of institutional and private actors."* [NASA-ESA, 2008]

Figure 5-29, Emerging Lunar Capabilities [NASA-ESA, 2008].

Note, once again, the lack of planning for the integration of commercial activities based upon tourism, settlement or SMR in the GES plan. Shortly after GES, in 2009, a detailed Canadian design reference mission (DRM) for lunar SMR and underground facility development was developed by Penguin Automated Systems of Sudbury, Canada under Canadian Space Agency funding.

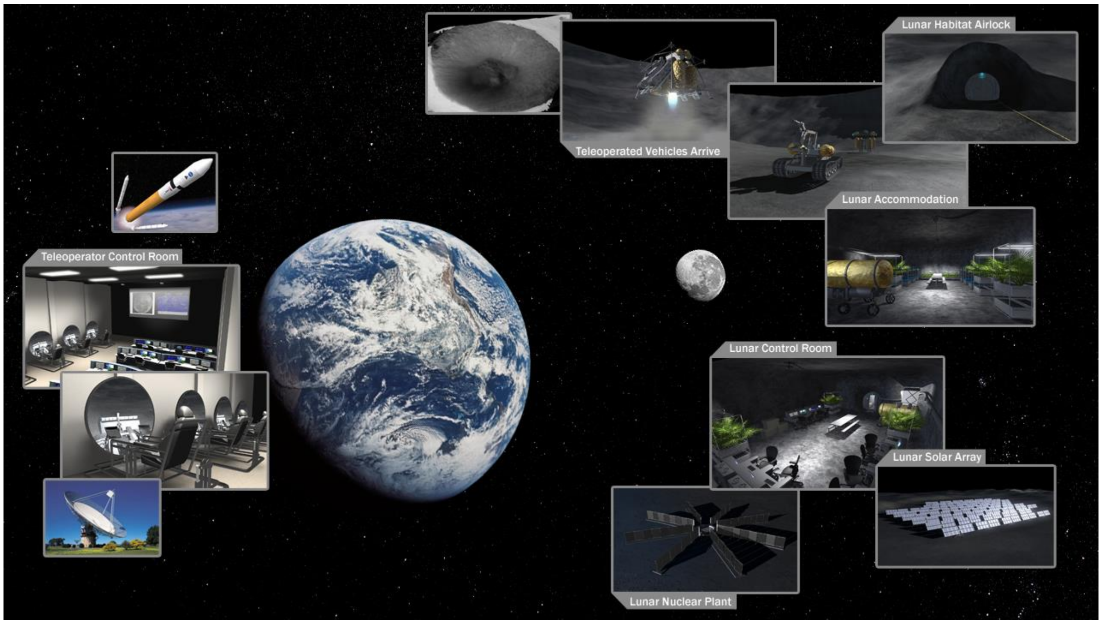


Figure 5-30 Primary Elements Underground Lunar DRM [Baiden, 2009].

The study, called SMART-STEPS, examined the preliminary design of an underground (radiation safe) lunar polar facility, developed models for mining equipment and operation sequences, and argued for government SMR technology investment based upon projected benefits to the Canadian mining industry [Baiden et al,2009]. Rationale for joint space mining and mineral processing technology with mining industry partners was also offered; and. discussions of the value of commercial partnerships were also included.

5.10.3 DRMs based upon in-space markets

The cost of delivering terrestrial resources into space is very high due to launch prices that remain expensive on a per-ton basis. Communications satellite companies pay US$60 million to US$150 million to place satellites into geosynchronous transfer orbits (GTO); and then, they have to allocate about one third of their satellite's mass to fuel to reach the operational geosynchronous orbit (GEO). This makes the true cost of placing terrestrial material (transponders, antennas, propellant, etc.) into GEO at least US$17 million per ton, even assuming the least expensive launch to GTO. A ton of anything in GEO thus has huge value – far more than a ton of silver on Earth (about US$1 million) — and within sight of the US$55 million price of a ton of gold on Earth.

DRMs based upon in-space markets are designed to deliver commercially valuable commodities and products to assorted space locations that have, or are expected to have, economic activity based upon commercial or governmental pursuits. These DRMs can be sorted on two axes: the in-space destination and the type of materials to be delivered.

Near-Earth Destinations. The space locations near Earth with the most activity today are low Earth orbits (LEO), such as traveled by the International Space Station and various remote sensing satellites in polar orbits; and GEO, where more than 400 satellites provide communications and imagery services to companies and governments. Because GEO is harder to reach from Earth than LEO, the value of asteroidal materials delivered to GEO is approximately four times higher than to LEO, making GEO satellites attractive initial customers. In addition, to move asteroidal materials from a high orbit (where NEAs will arrive) down to LEO requires effort to remove orbital energy. This makes the LEO market even less appealing compared to GEO. Countering this is the potential for growth in LEO demand as more companies and nations establish crewed outposts to exploit the rapidly growing list of microgravity opportunities in LEO for pharmaceuticals, specialty materials production, tourism, and other applications. Taken together, the destinations and markets described suggest the primary Design Reference Missions for Space-Based Markets, as described below:

DRM GEO: This location is closest to the largest existing in-space market for asteroid resources as it is reasonably high in the Earth's gravity well. Processing facilities likely would be established in the graveyard orbit 300 km above GEO where depleted comsats are stored to ensure any debris generated does not interfere with active satellites below. While it takes more energy to reach GEO than EML-1 from a NEA orbit, this is offset to an unknown degree by the fact that it is easier to reach from Earth (the source of the equipment and crews needed to operate materials processing facilities). In addition, the construction of large-scale industrial, observation or communication platforms in GEO using asteroidal or lunar resources would become an early milestone in the maturity of in-space customers.

DRM Space Elevator: There are two locations that are strategically significant when talking about the movement off-planet by the space elevator. The GEO Node is the key location for all business related to the Earth and its environment. This natural location would be called DRM SE-GEO and would enable commercial ventures to grow their businesses to enhance life on the planet. The second location would be DRM SE-AA. The Apex Anchor is located such that it is stable and is able to release and capture payloads going anywhere in the solar system. In addition, the spaceport at DRM SE-AA will be able to build exploration spaceships and repair or update ones returning to the Earth ecosphere.

DRM EML-1: Destinations with far less current activity; but, it has the potential for growth that includes the Lagrangian points in the Earth-Moon system. These are balance points where spacecraft can maintain position with minimal expenditures of station-keeping propellant. As the Moon revolves around Earth, spacecraft or habitats in Earth-Moon EML-1 [EML-1] and EML-2 can maintain their relative positions to the Earth and Moon with minimal energy expenditures. Both have been considered useful staging locations for crewed expeditions to the Moon and Mars. EML-1 offers an attractive place to park arriving asteroidal material and conduct processing, as well as to stage propellant depot operations for lunar-derived fuels. Some output would serve local needs (to outfit missions to the Moon and Mars) while other products could be shipped to GEO and LEO. In general, the "higher" a location is in the Earth's gravity well, the less energy is required to reach that location from the orbit of a NEA – this favors EML-1 as the point of initial processing. However, the "best" trajectories to reach each potential receiving location, starting from a multiplicity of potential NEA orbits, are yet to be worked out. Due to low outbound energy requirements, EML-1 offers a unique opportunity to service many inclinations in Earth orbit without the usual plane change penalties. This makes it a valuable and unique location for inbound as well as outbound, orbital transfer. Indeed, an EML-1 traffic control authority will be an early policy requirement to minimize scheduling and operational conflicts. A strength of the lunar space elevator is that its stable point is coincided with the EML-1 location. As a result, the proposed spaceport would have a very stable location while attached to the lunar surface through the lunar elevator and it would have a simple up-down transportation infrastructure.

The Earth-Sun system also has Lagrangian points. Earth-Sun ESL-1 is the vantage point for the upcoming DISCOVR spacecraft, where it can look back at Earth and always see a fully illuminated disk. Earth-Sun ESL-2, which has the Earth constantly between it and the Sun – is a popular destination for infrared telescopes that need to stay as cold as possible. In this location, a sun shade can simultaneously block the heat emanating from the Sun and the Earth.

DRM Lunar Orbit: Low lunar orbit (LLO) is a destination that could serve future crewed and robotic activity on the lunar surface. Spacecraft taking off from the Moon might be fueled by propellant extracted from cold traps at the lunar poles; and, spacecraft descending to the Moon might use fuel produced from NEAs processed in lunar orbit. Other scenarios would have both Earth-Moon and Earth-Mars traffic routed via the Earth-Moon EML-1 point where NEA processing would deliver propellant useful on both routes. LLO is the least likely location to process asteroidal material for two reasons. First, it places processed asteroid materials in the Moon's gravity well, requiring energy to boost them out to markets. Secondly, there is no current local market to serve in lunar orbit. The lunar orbit is useful only to those heading to the Moon; Mars expeditions would not detour down into the lunar gravity well to get supplies. As noted earlier, even Moon expeditions would have more flexibility in reaching diverse lunar surface destinations leaving from EML-1 than from a fixed lunar orbit. In addition, the instability of Lunar Orbit due to gravitational anomalies on the lunar surface (called Mascons) makes its long-term use hazardous.

5.10.4 DRMs based on terrestrial markets

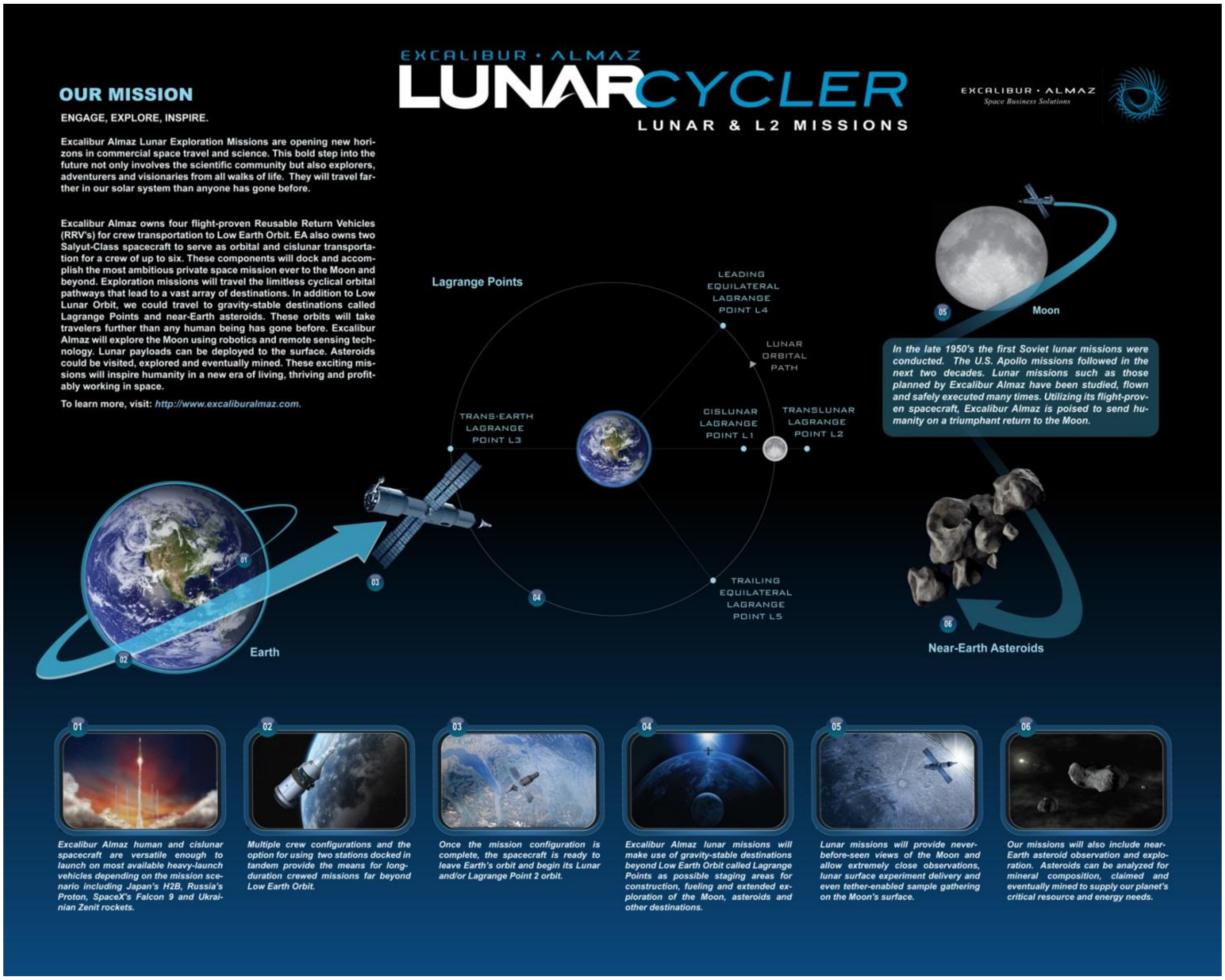
The return and sale of asteroid materials into terrestrial markets has been underway for many years. Asteroids are the only SMR with its own sample return program. About 100kg of meteor samples rain down upon the Earth annually. As costs for space infrastructure drop, the number of asteroid-derived products sold on Earth will naturally increase. Short-term terrestrial markets for samples *deliberately collected and returned* could include: Samples for science & collectors, PGMs, REEs, Nickel & industrial metals, microgravity-processed materials (e.g., protein crystals), other biological research, etc. Longer term markets could include lower value materials.

> *"Last but not least, there are also strong environmental arguments for mining even relatively common materials (such as iron, nickel, copper, and the increasingly important rare earth elements) from asteroids as an alternative to invasive strip-mining on Earth – asteroids do not have indigenous ecosystems that may be disrupted by mining activities whereas our planet does (see the discussion by Hartmann, 1986). For all these reasons, developing the capability of extracting useful resources from asteroids, and from other extraterrestrial sources, can be seen as an important investment in the future of the world economy (e.g. Crawford, 1995)."* [Crawford, 2013]

Long-term terrestrial markets could include: Industrial products and specialty manufactured goods. The NASA NIAC Robotic Asteroid Prospector project recommended a process for evaluation of these elements, analyzing the value of PGMs and REEs returned to Earth from a near-term mission. Note that the NASA microgravity research program (1998-2004), ISS Program Office, and Space Partnerships Program have conducted significant research for potential products made in space & returned to Earth. Many of these could be reevaluated for SMR contribution.

> *"We will leverage the lessons learned from government-sponsored space programmes to the maximum. After a phase of robotic prospecting, our crews will establish the infrastructure in space and base camps in the lunar polar crater regions to supervise industrial machinery for mining, processing and transporting lunar products to market in Low Earth Orbit (LEO) and beyond. It is essential that we seize this opportunity now to provide low cost propellants in space as a means to jumpstart the new space economy." – Dr. Bill Stone* [Stone, 2011].

The value of SMR is foundational to a thriving space economy. Who will use these propellants? Tourists can achieve leverage from SMR to extend the reach of their sortie missions to and around the Moon and beyond. Excalibur-Almaz corporation, based on the Isle of Man, is now offering circumlunar tourism based upon already built & tested privatized Russian spacecraft [Excalibur Almaz, 2013].



OUR MISSION

ENGAGE, EXPLORE, INSPIRE.

Excalibur Almaz Lunar Exploration Missions are opening new horizons in commercial space travel and science. This bold step into the future not only involves the scientific community but also explorers, adventurers and visionaries from all walks of life. They will travel farther in our solar system than anyone has gone before.

Excalibur Almaz owns four flight-proven Reusable Return Vehicles (RRV's) for crew transportation to Low Earth Orbit. EA also owns two Salyut-Class spacecraft to serve as orbital and cislunar transportation for a crew of up to six. These components will dock and accomplish the most ambitious private space mission ever to the Moon and beyond. Exploration missions will travel the limitless cyclical orbital pathways that lead to a vast array of destinations. In addition to Low Lunar Orbit, we could travel to gravity-stable destinations called Lagrange Points and near-Earth asteroids. These orbits will take travelers further than any human being has gone before. Excalibur Almaz will explore the Moon using robotics and remote sensing technology. Lunar payloads can be deployed to the surface. Asteroids could be visited, explored and eventually mined. These exciting missions will inspire humanity in a new era of living, thriving and profitably working in space.

To learn more, visit: *http://www.excaliburalmaz.com.*

In the late 1950's the first Soviet lunar missions were conducted. The U.S. Apollo missions followed in the next two decades. Lunar missions such as those planned by Excalibur Almaz have been studied, flown and safely executed many times. Utilizing its flight-proven spacecraft, Excalibur Almaz is poised to send humanity on a triumphant return to the Moon.

01 *Excalibur Almaz human and cislunar spacecraft are versatile enough to launch on most available heavy-launch vehicles depending on the mission scenario including Japan's H2B, Russia's Proton, SpaceX's Falcon 9 and Ukrainian Zenit rockets.*

02 *Multiple crew configurations and the option for using two stations docked in tandem provide the means for long-duration crewed missions far beyond Low Earth Orbit.*

03 *Once the mission configuration is complete, the spacecraft is ready to leave Earth's orbit and begin its Lunar and/or Lagrange Point 2 orbit.*

04 *Excalibur Almaz lunar missions will make use of gravity-stable destinations beyond Low Earth Orbit called Lagrange Points as possible staging areas for construction, fueling and extended exploration of the Moon, asteroids and other destinations.*

05 *Lunar missions will provide never-before-seen views of the Moon and allow extremely close observations, lunar surface experiment delivery and even tether-enabled sample gathering on the Moon's surface.*

06 *Our missions will also include near-Earth asteroid observation and exploration. Asteroids can be analyzed for mineral composition, claimed and eventually mined to supply our planet's critical resource and energy needs.*

Figure 5-31, Lunar Cycler [Excalibur Exploration, Inc.]

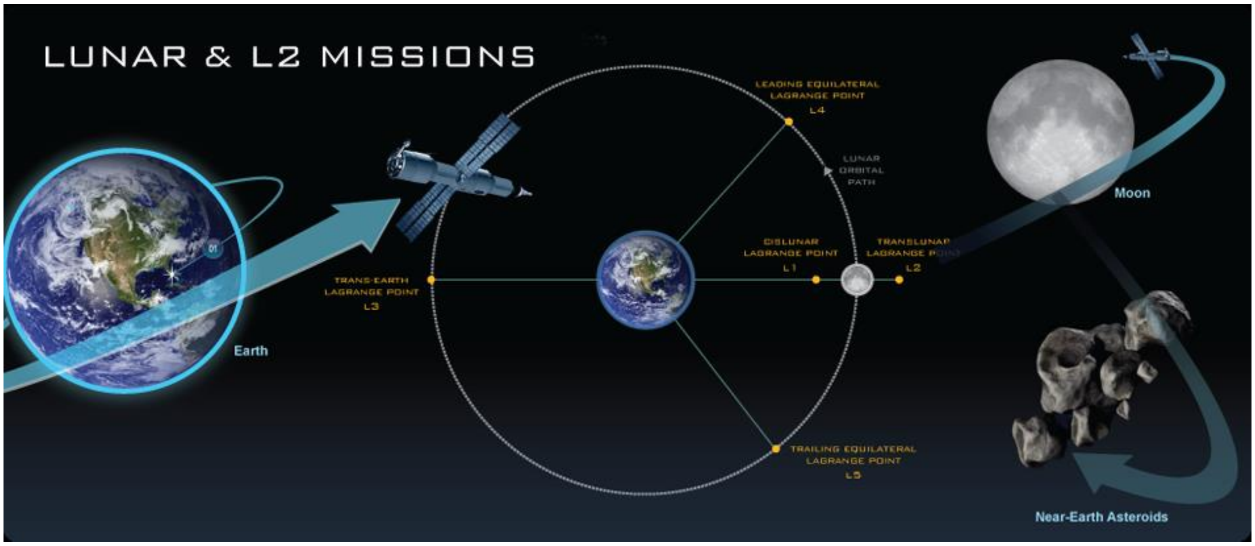


Figure 5-32, Lunar and Asteroid Tourism [Excalibur Almaz, 2013].

Mars-bound settlers will no doubt benefit from, and indeed even form a robust market for, SMR-derived propellants. Recent announcements by SpaceX founder Elon Musk of his desire to build a 10,000-strong Mars colony within his lifetime carry significant weight. The number of people who have already signed up for Bas Lansdorp's Mars One one-way mission has already exceeded 200,000 people – a clear indication that risk preferences for human Mars exploration are loosening [Wong, 2013].

5.11 Asteroid Nickel Process DRM

This section examines the technical and preliminary design requirements for a nickel carbonyl processing system for use on a 'typical' chondrite asteroid. The current unknowns in the Excalibur Exploration (EE) asteroid nickel architecture include technical details about the processing and production circuits, including masses, energy consumption and costs. These unknowns can be mapped onto a well-known product in a well-understood terrestrial marketplace using a set of operations research tools. This section outlines a sample approach to produce nickel for sale in space. Primary features of a generalized systems model will result from environmental physics, technical state of the art, legal environment, economic conditions, and timing. Constraints will arise from these primary features and their present and projected future conditions. Propagation of these constraints can be achieved through examining and modeling their interrelationships, for example the time value of money, or the role of law in reducing economic risk. Physics offers a well understood set of mathematical tools to map interrelationships between the environment of space (including its mineral and energy resources) and the technical state of the art (which is a function of time and investment).

MINING & PROCESSING ELEMENTS

Asteroid mining begins by defining or assuming the class of the target asteroid – its general properties (type & location) as well as specific assumptions including ore grades in parts per million (ppm). Environmental physics can help further define and map the energetic (e.g. range of solar flux), geochemical and geomechanical (rock strength & fragmentation state) properties that will limit or enable mining and processing. An in-situ processing plant will be required for extraction & refining of the ore into a product. Future technical states of the art and process efficiencies can be approximated by using ROM estimates and power laws to extend terrestrial industrial processes and principles into anticipated future conditions. The design process can then begin to take hold, revealing details about what is possible and what is not.

Working the technical problem starts with the customer. By examining current economic conditions for Nickel on Earth, a forward projection can be made to set production and price targets. Ten percent of today's annual market is ~160,000 tons. At roughly $20,000/ton this would generate a $3.2 billion payoff. Thus, the production of a commodity from asteroidal materials enables the identification of both technical and cost targets. This section will deal with the technical side first. Dividing this into 10 shipments yields a design goal to generate a 16,000 ton ingot of pure Nickel.

"Most types of noncarbonaceous asteroids are expected to be rich in nickel-iron (NiFe) metal. Carbon monoxide is a nearly ideal reagent in the processing of NiFe, via the carbonyl process. The process works at low temperatures, requiring little power or cooling equipment. It works at modest pressures, thus allowing an inexpensive reaction vessel. Best of all, it produces finished metal goods from unrefined NiFe in a single process step (Lewis and Nozette 1983; Lewis et al. 1988)." [Nichols, 1993]

In general a nickel carbonyl processing facility will require three primary elements: A digestion process, a precipitation process and a distillation or gas phase separator. Support systems will include heating, power, pumps, fluid lines and other infrastructure.

Nickel Digestion

At temperatures of 60c, carbon monoxide (CO) gas reacts with solid nickel to form nickel carbonyl gas Ni(CO).   Dissolving native nickel at this temperature might be as simple as putting a plastic bag around the asteroid and creating a flow regime. Again, the SETI Institute's SHEPHERD Concept has a solid systems approach for the approach, capture, stabilization, and extraction of volatiles. [Shepard, 2014] The encapsulation of the asteroid can be shown in the following three images so that an enclosed environment exists for the exploitation of the volatiles. [Images approved by SETI Institute for use in this IAA Study]

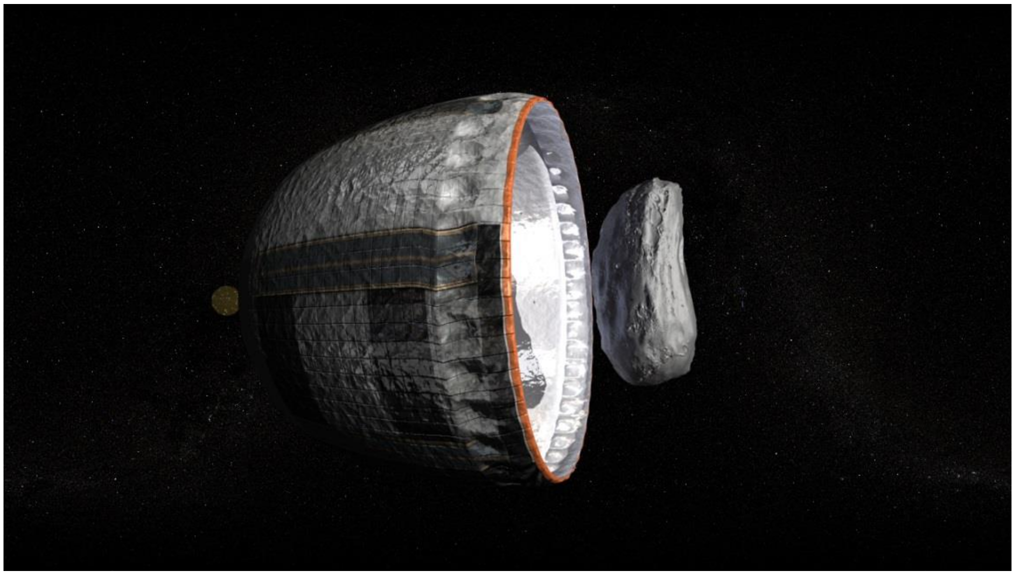


Figure 5-33, Capturing the Moving Asteroid

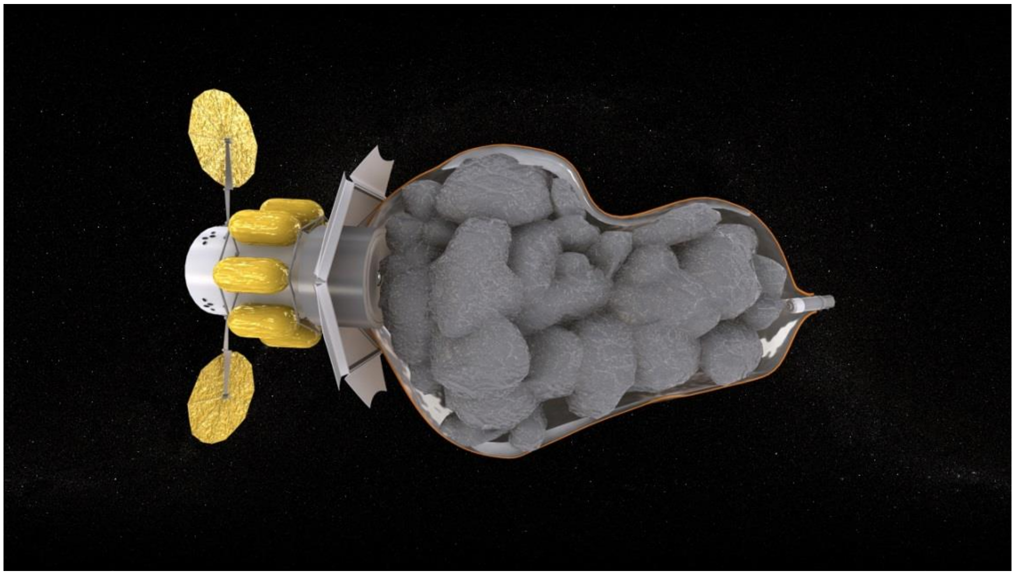


Figure 5-34, Enclosing the Asteroid with a Sealed Bag

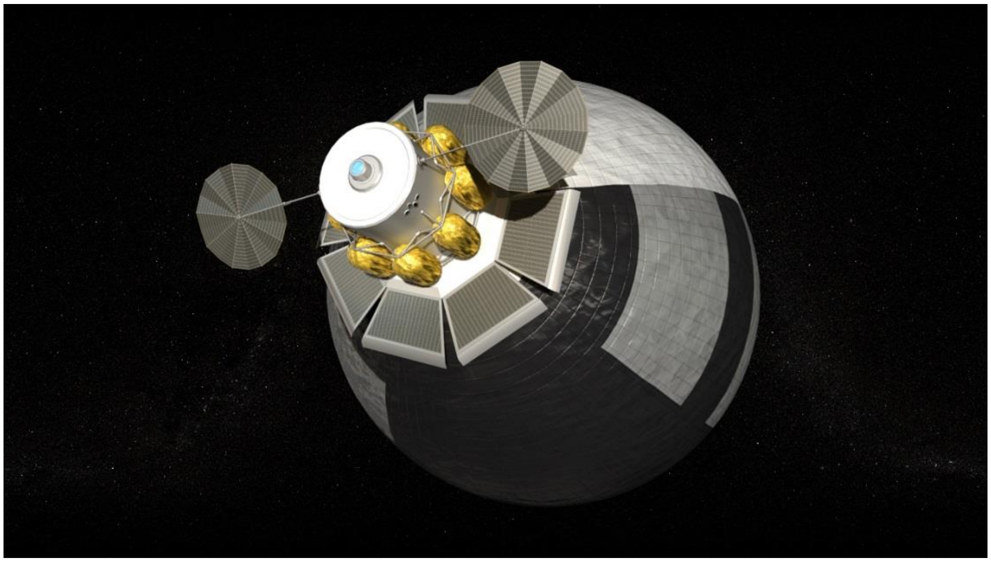


Figure 5-35, Power and Thrusters for Movement of Captured Asteroid

By allowing visible light to transmit through an interface such as thin plastic while reflecting infrared radiation from the same interface it could be possible to create a passive heating mechanism to start the nickel digestion. Feasibility analyses for such a system would start by examining transmission and reflection wavelengths (one could think of this as a bandpass filter) and insulation values. The wavelength of maximum thermal reflection can be derived using Wein's Law. Based upon the high degree of warming due to the atmosphere of Venus, and the average starting temperature of a low-reflective body (specifically the Moon – with an average surface temp of 0 centigrade), it appears possible that an asteroid that is highly absorptive of visible radiation combined with at least a greenhouse insulator could reach the reaction temperature of 60 centigrade using passive means. Note that asteroid reflectivity could be dramatically reduced by applying a thin coat of carbon soot onto its surface, increasing the heating rate. Heating rate and maximum temperature could also be augmented by an inflatable solar concentrator if need be – this could be the same concentrator assumed to work for nickel deposition used in a pre-heating mode. The question is - if a passive heating system (e.g. plastic bag with greenhouse effect) were put around the asteroid, how much nickel carbonyl gas would emerge, how fast, and what other components would also come out? It is recommended that this be studied in more detail to determine its feasibility. The digestion process may have CO purity requirements - secondary gases produced with greenhouse or solar concentrator heating could poison the carbonyl digestion reaction and may need to be flushed out first. Carbonaceous chondrites may already have carbon monoxide in them in addition to native nickel [Nichols, 1991, p. 546]. Industrial refinery experience can show us how to make CO from other hydrocarbon processes – it is relatively straightforward. The good news is that it appears to not take much CO to make the process work and (other than leakage) the CO used can theoretically be fully recycled.

"The carbonyl process consumes very little carbon monoxide. The only loss is the tiny percentage remaining in the ore and the metal product. Thus a very large foundry could operate with a small input of makeup gas. This is actually an argument against mining asteroids for carbon monoxide alone, because the amount needed could be brought from Earth at reasonable cost. However, because carbon monoxide will be a by-product of other processes, its production is essentially free." [Nichols, 1991]

An estimate of how CO propagates trough soil mass will need to be created. This will be measured as liquid or gas permeance – one can look up numbers from hydrology or oil & gas fluid dynamics to get started. Meteorite samples can also be used to experimentally determine a range of likely values. Note that gas travels through a soil mass faster than liquids. Related questions include: What other gases will come out if the temperature is raised? And how much does fracturing change this flow rate? Note that the plastic bag could be cinched to create a choke point for creating a pressure gradient.

It will be important to find or engineer a method of creating a pressure gradient. The YORP effect already causes a temperature gradient – it will be important to adapt 3D thermal models of this effect for starting a gas evolution and CO temperature / pressure / flow gradient model for the digestion process. Questions include: Can we mix a material onto the surface to increase solar absorption? (Maybe all we need is a good paint job). Are there natural heat amplifying geo-features such as specific types of boulders?

The size of the greenhouse bag would have to be larger than the target asteroid, with thickness and reinforcement determined by anticipated wear and abrasion estimates. Mechanisms for maneuvering the bag around the asteroid would have to be designed and a sealing and cinching mechanism developed. Reinforced polypropylene could be used for containment, provided it can stay flexible in a vacuum.

Nickel Precipitation

Depositing Nickel from carbonyl gas is straightforward and can produce pure nickel on a substrate or precipitate nickel powder depending upon temperature. Once pregnant gas is extracted, it needs to be cleaned and reused where the nickel is deposited and CO comes back off the reaction. The shape of the final device could be as simple as a thin plastic form inflated by the carbonyl gas. Input & output flowrates will define the minimum size of the orifice (the orifice cannot be clogged or the reaction will stop). Heating will need to be done for the outside of the shape or form. Resistive heating or solar thermal might do the trick. It will be important to understand how this process is done in industry today. Microwaves might also work. Once nickel starts plating, it should distribute the heat quite well and keep the plating going. It will be important to estimate time and heat loss rates - these will directly convert to energy requirements for the design of support spacecraft.

The form could be a simple or complex shape and will require uniform heating for deposition of the same thickness of nickel everywhere. As a heritage system, technical details for the Echo 1 and 2 satellites might help in the design of the nickel deposition form. Specifically, the 30.5 meter diameter Echo 1 balloon was made of 12.7 μm metalized 0.2 μm thick biaxially-oriented PET film – commonly called Mylar and the balloon weighed 71.21 kg including 15.12 kg of sublimating powders [Wikipedia, 2014]http://en.wikipedia.org/wiki/Project_Echo]. These are giant balloons that were flown in space, which makes them a good analogy for the forms or surfaces that could be used upon which to deposit the nickel using the carbonyl process. Kapton might be a better material than Mylar due to its heat resistance. The differences need to be investigated.

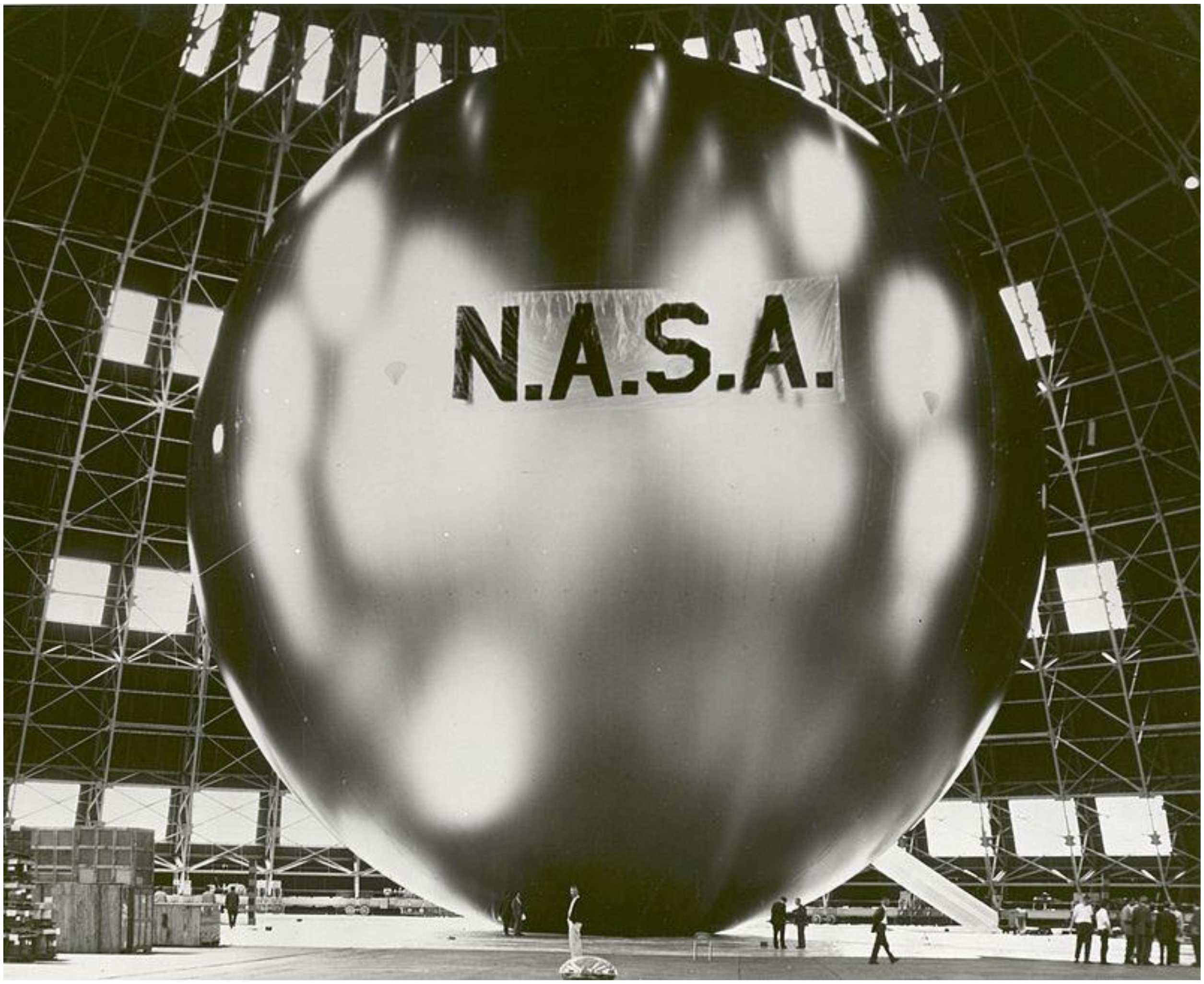


Figure 5-36, Echo Balloon Satellite [NASA image]

There's a refining facility that uses the monde process in Wales, UK that makes about 7.9 million pounds of nickel a month (47,000 tons/year). This is about 3% of world nickel production annually. Total Ni deposition mass over time is a function of the Ni plating surface area. This is why small pieces of nickel, dust and sand, pebbles rocks and chunks work best. Note that the surface area can be radically increased using fractal systems and metal foams, radically increasing the deposition quantity of structural nickel. Making nickel dust and packaging it inside a nickel metal package for delivery is desirable. The package only has to be about 5% of the total mass.

MODELING

A preliminary model was made of Nickel Carbonyl digestion and deposition to incorporate the variables above and examine the feasibility of using the process for asteroid mining. Preliminary model findings include:

1. A 160 meter ordinary chondrite (87% of known meteorite falls) has sufficient resources to produce 16kT of nickel at 50% recovery and, on average would contain nearly 13T of PGMs (note: this is a minimum baseline for grabbing whatever asteroid is most convenient - ore grades could be much higher if an actual exploration phase is undertaken - the reason this strategy works is that you can get nickel from almost any asteroid you find)

2. The most likely PGM tonnage per 16kT Ni = 12.9 tons; but, separation will be a BIG issue and require mechanical crushing, separation, concentration and serious complexity. The authors suggest not doing this part in any early demonstration.

3. An ordinary chondrite is likely to have enough CO in it to get the process started without bringing any reagents, at a temperature where the CO grabs the nickel using a plastic bag that allows visible light to enter and reflects infrared (thus leveraging the greenhouse effect for passive heating)

4. The time to produce a "pure 16 kton ingot" of 20 m sphere is 40+yrs (6mm/d is the max deposition rate of nickel metal) - this is a serious constraint

5. The production time can be dramatically reduced if "nickel powder" is produced (note that the powder is much lower in density but can be supported by an outer shell of pure nickel; and, the powder has unique uses such as in batteries and as a catalyst. The point is that it can be made much faster than vapor deposited pure metal on a substrate or form). However, the extra energy for this production rate increase has not yet been estimated.

6. So far it appears that the ore processing and deposition only needs a couple of plastic bags (rather large ones), a carbon monoxide "maker" and pump, a solar concentrator for heating, and a distillation unit to separate process "contaminants" (a.k.a. other valuable products like water).

7. The mass of outbound systems appears to be completely scalable. At first glance, it appears that a system to produce the 16kT ingot might be small enough to fit an existing launch vehicle (assuming a single stack constraint).

8. Chemical engineering will be required to define the distillation, CO making, digestion & deposition steps in more detail (the biggest WAGs with the highest uncertainty right now are the assumptions about energy / thermal management. A detailed design will be needed, especially with regard to the rate of nickel powder manufacturing).

9. An optimal asteroid might be represented as: High nickel (+ platinum group metal) content with plenty of CO or CO precursors. A small body (bag-able) is preferred; with, the more fractured or fragmented the higher the reaction rates. An asteroid that needs crushing is not desired as it will be a much more costly operation.

10. Testing on the ground using existing meteorite samples would give certainty (i.e. reduce risk) and critical data on one of the most important variables, the degree of fragmentation of the ore. Testing on the ISS would further reduce risks and produce PR opportunities at low cost.

TRANSPORTATION

An aiming / steering and propulsion system will be required for Earth departure from the asteroid mine-site. Aspects related to orbital mechanics will need to be designed by someone who is qualified to do so, an astrodynamicist, particularly for proximity operations. Some astrodynamical relationships have already been worked out for specific targets. These can be used as starting points for iterative design. With well-understood delta-Vs, an estimate can be made for the amount of water (likely already in the asteroid) propellant is needed for a return. Another important variable is the timing of outbound & return trajectory. Time value of money will be a critical input to a financial model. The destination would be EML-1 until safe return to the surface of the Earth can be arranged.

ECONOMIC FEASIBILITY APPROACH

The recommended approach for building an asteroid nickel economic strawman would be to:

- Create a technical model estimating mass, power and cost for key architecture elements (see above for a start on this);
- Create a demand model estimating throughput and revenues;
- Add dials to both models to ramp up or down key variables (this is a control page in Excel);
- Create a feasibility page that balances costs & revenues in time;
- Solve for the conditions under which the venture makes money; And,
- Evaluate what it would take to make said conditions real.

Primary elements of a comprehensive economic model will include technical, economic, operations and policy elements. Technical elements will include asteroid resource geologic assumptions, mining and mineral processing systems, transportation elements, astrodynamics and details on payload delivery characteristics. Economic assumptions will include products, price and quantities, customer profiles and contextual variables such as assumed discount rate, taxes and financing as well as risk assumptions and preferences. Operational assumptions and concepts will include mission timeline, direct labor vs. automation level, sequencing and control architecture. Policy, governance and management assumptions that will influence short v. long term mission success will include legal environment (e.g.

property rights, friendliness of host govt., etc.), existence and nature of contracts (especially with customers, but including suppliers and partners), patents and strategy for benefit sharing. It is assumed that investment in mining and transportation scales linear at worst case. The potential for economies of scale, at the best case, due to a learning curve and for an assembly line. Thus, ten mining / processing units will be deployed in the yearly operations model at ten times their unit manufacturing cost.

Chapter Six, Modeling and Analysis

6.0 Introduction

In reality, the movement to a profitable space mineral resource business will consist of three phases:

Phase One: Popularize the concept – Development of the approach, lowering the risks, and gaining initial funding.
Phase Two: Prototype Proof-Test – Initial resource acquisition and processing with some sales of initial product. This must lead to large investments in the concept.
Phase Three: Production –Major mining facilities providing product to paying customers.

This chapter will economically model the third phase of an SMR commercial venture. Predicting the near future is difficult – predicting the far future is rife with major miscalculations. This report has taken the position that two varied examples may be the best way to show the future. The authors have chosen to: 1) summarize a NASA study called Robotic Asteroid Prospector [RAP], and 2) calculate the required flow of water for the Elon Musk vision of 10,000 colonist on Mars. The first study was conducted with the approach of designing a working satellite architecture; and thus, showing the cost of accomplishing a fuel depot at the Earth-Moon EML-1 location [EML-1]. The second will estimate the needs of 10,000 people moving to Mars over the next 60 years. The question in both cases is how much water is required at EML-1 and how best to supply it. Both came up with the same conclusion, processing water for fuel, oxygen, and drinking can provide major profits for SMR companies mining asteroids.

Supplying water at EML-1 opens up the solar system!

This chapter will discuss the assumptions leading to both sets of results. The authors realize that the future will not unfold as shown; but, this can be used to recognize the dramatic economic viability of processing SMRs, transporting them to the customer, and selling the product at a spaceport.

Our first example, the NASA RAP study, shows that the process is achievable with profit as the motive. The second example requires an economic analysis that distributes people throughout our Earth-Moon-Mars region and "sells" water to the people moving between locations. The SMRs are processed on the Moon and Mars as in-situ resources; and most importantly, water [and other SMRs] are processed on asteroids. The obvious conclusion of any analyses that takes into account the movement between orbital locations is that "no gravity well leads to low cost of transportation!" Water is moved to many locations and sold to the customer in at least three forms: drinking water [also used for radiation shielding], air [major consumable is resupplied], and fuel [oxygen and hydrogen]. In chapter 3, the authors estimated the cost of lifting a metric ton of water from the surface of the Earth to multiple locations. That table showed the cost of water delivery to an EML-1 refueling depot, from the Earth's surface, as roughly $ 20 million (US) per metric ton. Obviously a profitable business would result if the sales price of water at EML-1 was less than $ 20 million (US), with significant margins for profit. This idea is not new; and, it is shown in Figure 6.1 from an older study.

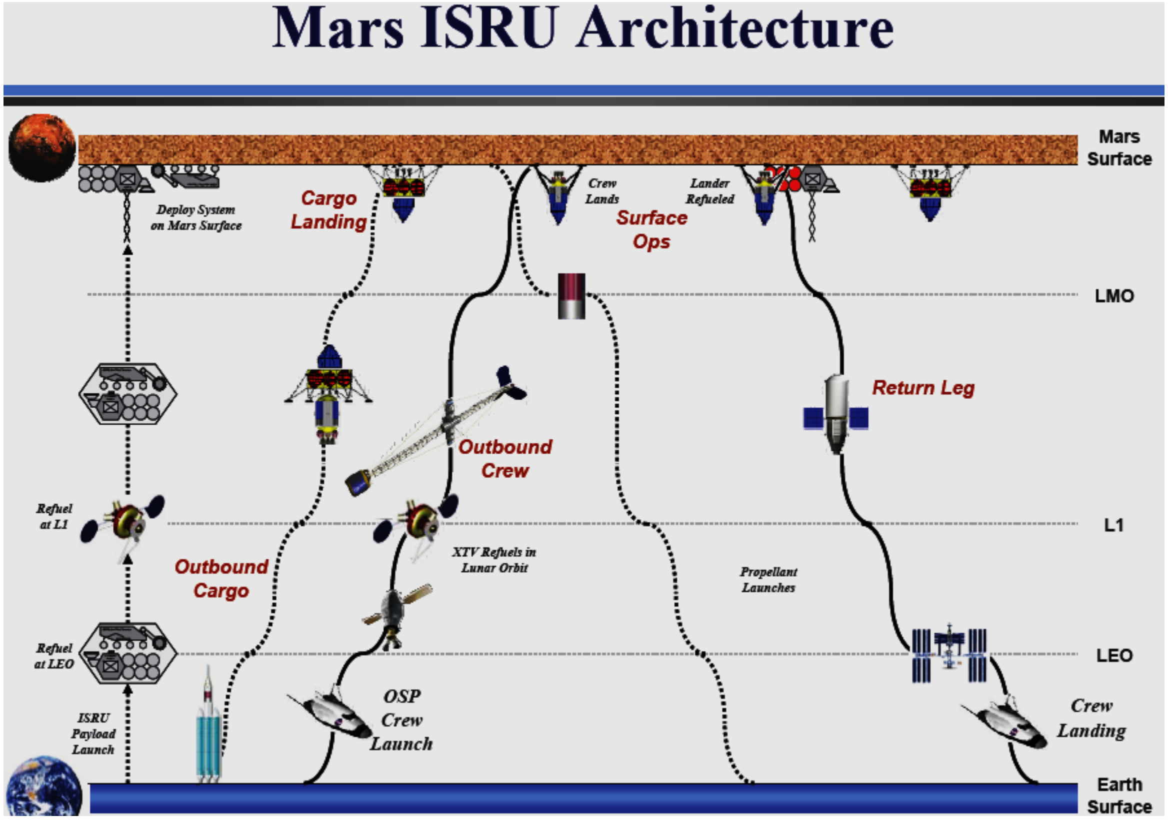


Figure 6-1, **Modeling SMR Market Development [NIA]**

To initiate the economic modeling of SMR activities, the authors summarize a recent NASA study on that very topic. This NASA Innovative Advanced Concept [NIAC} was conducted between 2012 and 2013 and resulted in similar conclusions to this Academy Study.

6.1 Robotic Asteroid Prospector, 2013

NASA recently completed a detailed study on commercial asteroid mining based upon the Robotic Asteroid Prospector (RAP) architecture, including an economic analysis of feasibility. The contractor team designed and assessed the cost of a set of spacecraft to get the asteroid mining job done, while also evaluating commercial markets on Earth and in space to set a relevant economic context for the design effort.

> *"Their proposal studies the fundamentals of some major questions facing the asteroid mining industry. What kinds of mission and spacecraft design are necessary? Is the right kind of mining technology available? And most importantly, is there even a viable business model for doing it in the first place? Dr. Cohen himself is skeptical that there is, but points out that's part of the reason he's so*

> *interested in performing the research. Contributing to his skepticism are the numerous assumptions the proposal is based on. These include a telescope in Venus orbit to help the search for near-Earth objects (one of NASA's primary mission statements, and similar to the B612 Foundation's space telescope that will hunt for Near Earth Asteroids) and regular commercial access to a service base located in a Lagrange point from which to launch the missions. "We're trying to make the assumptions really clear, specific and explicit, so we understand what the trade-offs are," Dr. Cohen told Universe Today. "One thing we're being very careful about is not going in with any preconceptions." The assumptions lead to a spacecraft design, possibly using a solar-thermal propulsion system, that launches to a NEO from the Lagrange point station, mines and processes the material at the asteroid and then returns it to the Lagrange point for shipment back to Earth."* [Tomaswick, 2012]

The technical strategy for designing the RAP mining spacecraft leverages SMR by using some of the extracted asteroidal water in its solar thermal propulsion system to return payload (water and precious metal cargo); thus, boosting performance through the clever use of the target asteroid's resources. Figure 6-2 below shows the basic spacecraft design. Note the two large solar concentrators and the asteroid payload bay. For asteroids larger than 20 meters in diameter, a companion spacecraft would be needed to break off a ~20 meter piece of the asteroid for processing.

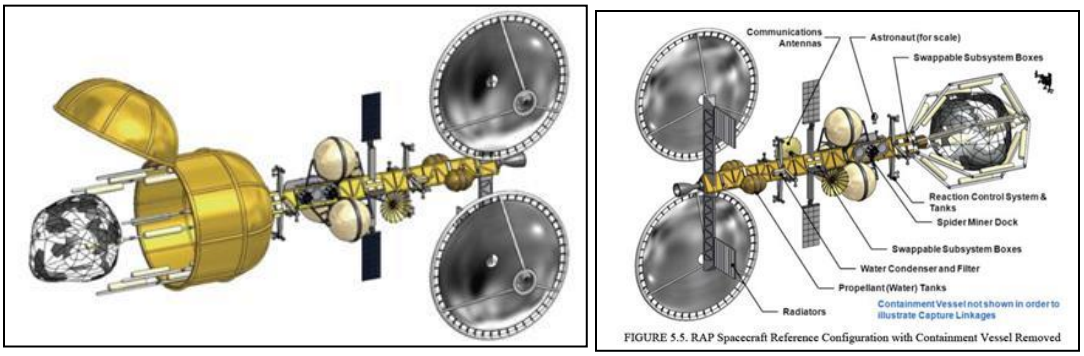


FIGURE 5.5. RAP Spacecraft Reference Configuration with Containment Vessel Removed

Figure 6-2, RAP Spacecraft Design [Cohen, 2013b].

The astrodynamics of near-Earth asteroids (NEAs) were carefully considered in the design and sizing of the spacecraft and its components.

> *"For any interplanetary mission the orbital position of the departure and destination objects drives the energy cost of the mission. Having selected a destination there is little flexibility in selecting a departure time. Moreover, the time between mission opportunities is driven by their synodic period, which can be extremely long, i.e. decades or longer, for objects with similar orbit periods. Therefore, the RAP mission architecture encompasses a highly flexible approach to defining mission opportunities that makes uses of multi-body gravity assists, multi-revolution interplanetary transfers and deep space maneuvers to maximize the number of mission opportunities while minimizing total mission Delta V."* [Cohen, 2013b]
>
> *"The challenge of asteroid mining can be decomposed into four key efforts including mission and trajectory design, spacecraft design, mining and processing technology for microgravity and vacuum operations, and how these efforts can add up to a business case. … This market assumes that the water collected from carbonaceous chondrites, from regolith ice, or from chemically bound sources, can serve as propellant with little or no post-extraction processing."* [Cohen, 2013b]

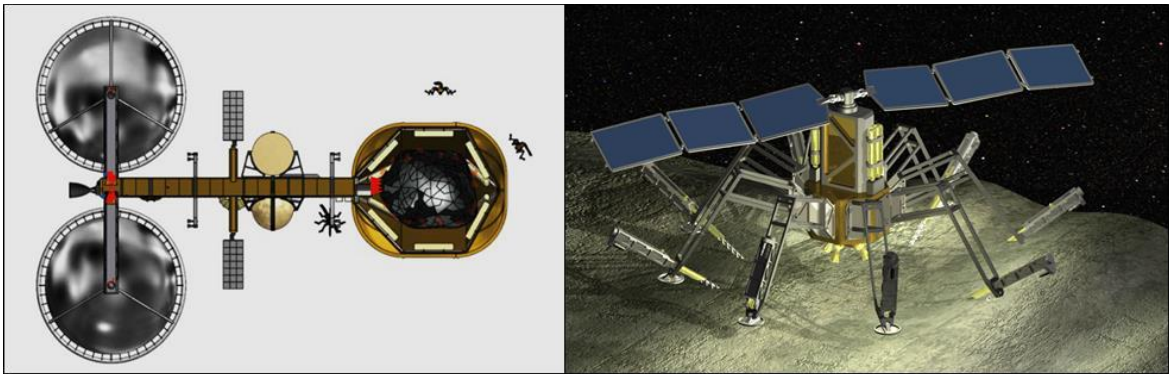


Figure 6-3, RAP Asteroid Mining Architecture [Cohen, 2013b].

Due to availability of design details and operations concepts for both small (<20M) and large (>20m) asteroids, the RAP architecture has value as the Strawman SMR economic study. Further, the RAP architecture leverages asteroidal water resources to extend its reach farther than other mining systems concepts available in the open literature – giving it a strong competitive advantage.

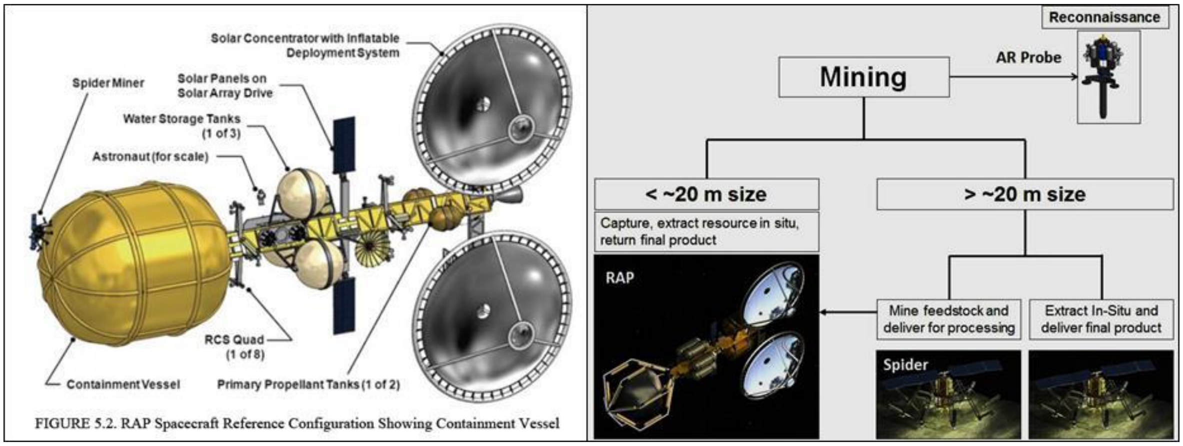


FIGURE 5.2. RAP Spacecraft Reference Configuration Showing Containment Vessel

Figure 6-4, RAP Spacecraft and Asteroid Strategy [Cohen, 2013b].

The mining strategy can capture small asteroids or extract a piece of a larger one. Subsystem design by Honeybee Robotics of Pasadena, California included drilling, auguring, anchoring and water extraction capabilities.

RAP Architecture & Spacecraft Engineering

The design of spacecraft reflected the need to combine transportation, mining, extraction and product delivery into one integrated vehicle.

> *"The RAP team designed a prototype prospecting and mining spacecraft. Its key features are the implementation of a solar thermal propulsion (STP) system incorporating parabolic solar concentrators that can concentrate sunlight to 10,000x the incident insolation. The design of the RAP spacecraft enables use of this concentrated sunlight in three ways. First, it provides the heat at up to 2500K to the solar thermal engine to expand the fuel out the nozzle to create thrust. Second, it provides process heat to the on board mining, extraction, processing, and refining systems. Third, it can generate about one megawatt of electricity using a Stirling cycle engine. Water is the preferred fuel for the RAP STP system because it has several advantages when compared to conventional propellants. It is very dense when compared to its cryogenic by-products liquid oxygen (LOX) and liquid hydrogen (LH2). Not only does it not require the complexity and cost of electrolysis followed by cryo-cooling, but also the mass of the water tanks can be much*

> *smaller than the tankage required for a comparable mass of LOX and LH2. Moreover water can be stored in flexible tanks that simplify the task of propellant management in zero gravity but which also can be launched into space in a collapsed state."* [Cohen, 2013b]

Delta V's (ΔV) utilized for preliminary RAP system sizing were based upon multiple previous asteroid mission studies. The Earth departure baseline would start at an Earth-Moon Lagrangian point (e.g. EML-1) and was sized for departure at –3.5 km/s of outbound ΔV. Asteroid capture ΔV was base lined at ~1.250 km/s, with asteroid departure at ~1.350 km/s. Propellant for departure using the RAP architecture would be derived from the local asteroid resources (providing the right type of asteroid is mined), and could be adjusted upward if needed. The Earth return delta-V baseline was ~2.5 km/s, reflecting reduced ΔV for capture to an EML. Additional ΔV could also be accommodated by adding/resizing propellant tanks or trading payload for propellant [Cohen, 2013a].

The RAP architecture cleverly incorporated SMR not only as a customer, but also as a fundamental part of the propulsion strategy, effectively trading increased transportation systems technical risk with the reward of much higher performance. Four years were allocated for each asteroid mining mission with three years budgeted for flight operations and one year for refurbishment/servicing. The complete RAP mining system was base-lined to return 150 metric tons of salable water to EML-1 along with sufficient water to support the next outbound journey of that spacecraft. Figure 6-5 below summarizes the demand modeling approach.

Figure 6-5, RAP Market Structure [Cohen, 2013a].

Earth markets for asteroid-derived products studied by RAP included Rare Earth Elements and Platinum Group Metals. Space markets were examined for water, agricultural soil, metals for construction and shielding materials.

> *"The RAP team identified water as the commodity most likely to be of value for extraction and sale to customers in space for use as propellant. Platinum group metals (PGM) are the best candidates for potential sale on Earth, however the scope of the undertaking would require returning PGMs to Earth in the 10s of metric tons. Rare Earth Elements (REEs), although increasingly in demand on Earth, do not appear to be a viable candidate at this time because of the high cost and complexity of processing the ore. Additionally since the current cost of REEs extracted from the Earth is driven by the cost of the environmental remediation associated with that activity there is the very real chance that reducing those remediation costs would be a more cost effective way to increase the supply of REEs than asteroid mining. . Future potential economic resources included scientific samples, regolith for radiation shielding, structural elements such as Al, Fe, Si, and Ti, processed water for life support, and processed regolith for agricultural soil."* [Cohen, 2013b]

Conclusions from RAP included observations that REEs and PGMs were non-starters. The reader must remember this was a government study, not a commercial corporation looking to trade risk for future profits. No details were provided on rare-Earth element (REE) economics in the final report. However, they estimated that missions which relied solely upon PMGs being returned to Earth were not feasible. The market price of platinum at the time of the study, discounted by refining costs, was estimated to be $41,000/kg. If total mission cost was $750M per flight, and assuming a profit of 25%, the mission would have needed to return ~18.3 metric tons of pure refined platinum just to break even (note 18,300kg = 635,000oz or 10% of the 2012 global Pt supply). No information was provided on platinum extraction and refining assumptions, nor the total added mass of PGM concentrate that would have needed to be returned to a terrestrial smelter to generate the commodity. Examination of the in-space market for asteroid products went into considerably more detail.

> *"The economic premise of RAP is that humans will develop an infrastructure for living and working in space. In this century, this infrastructure will grow to support hundreds of people and eventually thousands of people across the Solar System. We composed a space infrastructure development framework to characterize the growth of this infrastructure both in time and in the number of people living continuously in space. These space settlers will create a demand for commodities processed and products manufactured in space. The earliest commodity for which we see this demand is water. Water exists on the Moon and in the asteroids. The Delta V to return water from an asteroid can often be less than to enter and escape from the Moon's gravity well. We believe that water from asteroids can present a comparative advantage over lunar water and an absolute advantage over water from the Earth."* [Cohen, 2013b]

The economic analysis for water mining assumed the chief competitor for asteroid-sourced water would be water delivered to space by a low-cost terrestrial launch system. This established a price point that the RAP architecture would have to beat. Using a simple technical argument, and based upon low launch prices offered by SpaceX, members of the team calculated that ~$20,000 per kg would be a reasonable approximate cost for delivering Earth-sourced water to EML-1. For economic feasibility, RAP would have to do better than that to be a success. The summary for the RAP business case used a Rough

Order of Magnitude (ROM) estimate for the cost of the asteroid derived water as follows. It was estimated that a 22 year program would consist of four mining spacecraft in 12 water recovery missions. The net water returned per mission would be ~150,000 kg. ROM estimates for costs were Total Expenses = $9.2B: (Development $2.5B, Spacecraft Production: $3.6B, Operations Costs: $3.1B, Total Expenses: $9.2B). The total water returned would be 1.8M kg or 1800 metric tons for the 12 mission set. The calculated RAP cost of water delivered to EML-1 would then be $5,100/kg. This figure did indeed beat the assumed competition (water from Earth at $20,000/kg). The team argued that water production could also be doubled without doubling the total costs, concluding that the system design needed to be refined and detailed so that formal cost estimates could be done. What was missing from the approach was the size or volume of a hypothetical space water market through time – a critical element of quantifying future demand.

With REEs and PGMs declared "non-starters," the RAP architecture would make no economic sense without establishing a customer basis for the in-space water demand. To answer this, members of the team offered a simplified "Space Infrastructure Development Framework" that could scale demand through time, showing a potential growth and an evolutionary path for in-space water customers.

> *"The RAP project's approach to understanding the prospective markets for space resources was to develop a qualitative Space Infrastructure Development Framework. … To envision the start of the deep space economy, the RAP team constructed this Framework to model the values and variables of nascent space commerce. This model describes the potential market, customers, and capital funding for the development of human habitation and industry in space. This human development will include space infrastructure, colonies, settlements, stations, and mining and processing operations."* [Cohen, 2013b]

Due to the detailed level of architectural and mining spacecraft design work, as well as the availability of preliminary cost estimates published by the RAP team, the architecture's cost and performance assumptions offer an important technical baseline for the systems analysis. A SMR systems analysis will utilize some of the technical conclusions, as well as the market and space infrastructure framework from the RAP study, including estimates of asteroid mining systems' cost and productivity.

6.2 Systems Modeling Framework

One approach to understanding future markets for SMR is to develop a modeling framework that can begin to quantify the anticipated demand behavior of future economic agents. This is the approach taken by members of the SMR team, which has created a Space Infrastructure Development Framework that will serve as a starting point, or reference model, for probabilistic demand modeling. To envision the start of a deep space economy, team members constructed this Framework to model the values and variables of nascent space commerce based upon the ultimate consumer: a future human space colonist. This model posits starting point estimates for potential markets, customer needs, and capital requirements for the development of human habitation and industry in space. This creates a starting point for an iterative process that can be used to solve for those very values. By assuming future demand, engineering and costing can begin to converge on whether that demand can be met in a profitable fashion, completing one iteration, or turn, of the model. Human space development will eventually include space infrastructure, colonies, settlements, stations, and mining as well as processing operations.

Quantitative Space Demand Modeling

An important and enabling assumption of SMR is that humans will progressively develop infrastructure for living and working in space. In the current century, this infrastructure could support from hundreds to thousands of people on the Moon, Mars, NEOs, and, eventually, grow to millions of people across the Solar System. A space infrastructure development framework is modeled, which shows transportation nodes and human settlement destinations in order to estimate the growth of infrastructure in terms of time as well as the number of people living continuously in space. These space settlers will serve as the basis for the demand of future commodities and products manufactured in space. By using human settlers as the basis for demand projections, standard methods and results of demographic analyses can be projected into future scenarios, thus creating a quantitative basis for predicting future commodity and end product usage that leverages current trends and marketing data.

The first anticipated commodity, with strong projected demand, is water. Water has been shown to exist on the Moon and asteroids in varying conditions and concentrations, including recently discovered high-grade deposits at the lunar poles. For certain asteroids, the Delta V to return payloads to a stable orbit in the Earth-Moon system (i.e. proximal to customers) from an asteroid could be less than to enter and escape from the Moon's gravity well. Although, many of these low-energy transfer opportunities can have a long waiting period. Under these conditions, water from asteroids could present a competitive advantage over lunar water. For customers in space, both sources offer an absolute advantage over water from the Earth in terms of the physics of mass transfer given current transportation technology. Translating advantageous physics into an economic opportunity, however, requires the right alignment of technology, cost and markets. The primary output of the Space Infrastructure Forecast (SIF) is the anticipated annual demand for water at various system nodes from Low-Earth Orbit to the surface of Mars. Water demand is expected to be driven by a combination of propellant refueling requirements and human consumption of air, water and food. In addition, a space infrastructure development framework based upon human consumption could also be expanded to accommodate other potential lunar or asteroid products including structural metals (Al, Fe, Mn, Ni, Si, Ti), platinum group metals (PGM), regolith for radiation shielding, regolith to provide soil for agriculture, and scientific samples.

Number of People Living in Space Continuously

An important variable of the SIF model shows the projected number of people living continuously in space at the end of each 15-year increment. This population forms the basis or source of demand for modeled commodities, consumables, or future products produced and delivered in space. This project uses the term continuously instead of permanently as the later would imply that the people would not return to Earth. Rather, the estimates assume there would be a given number of berths within a reusable transportation network that would be continuously occupied by crew members or inhabitants that would be free to rotate back to the Earth at the end of their "mission," tour, or sojourn. Therefore, the Space Infrastructure Forecast (SIF) would not require people to move "permanently" to space. The assumed start year for the model is 2010, roughly the date six people began living continuously on the ISS. The growth projection for 2025 shows a doubling to a value of 12; and then, into a gradual geometric increase in later periods due to the assumed increase in use of SMR for colony 'independence' from terrestrial constraints. By 2025, it is possible that more than one NewSpace company will become a contender to send humans beyond LEO (e.g. Excalibur-Almaz, Golden Spike, Shackleton, Inspiration Mars/Paragon SDC, SpaceX/Virgin Galactic, Bigelow, Boeing, and MarsOne). A risk-constraint framework would suggest that the likelihood of any one of them succeeding is the inverse of the number of contenders. It is also likely that some of the current actors will merge into larger teams than have so far been created for the NASA Commercial Crew and Cargo or Google Lunar-X Prize. As this series of estimates expands past 45 years, the average in space population extends to 26,046 humans. Admittedly, this analytical approach is crude and starving for data; but, it helps to provide a framework to conceptualize a deep space infrastructure and the economy that will demand it. It serves as a point of departure for calculating the engineering and technology requirements to serve that potential human population.

A mathematical modeling approach is offered to solve for feasibility conditions. The assertion is made that engineering, costs, markets and the influence of policy on systemic risk can be quantitatively modeled. Model fidelity vs. uncertainty is clearly a function of the modeling effort, which is at a very high-level for this preliminary stage of the game. The use of approximations enables a basic modeling framework to be assembled and upgraded as work effort is expanded to improve model fidelity. Transparency in reporting variables and relationships enables reviewers to check whether the basic technical and financial assumptions are reasonable. It also gives decision-makers a framework from which to evaluate risk buy-down (e.g. changes in law & policy or technological maturation) as well as confidence-building (e.g. marketing & customer evaluation) strategies.

One workable and rational approach to understanding future markets for SMR would be to develop a modeling framework that can quantify the anticipated demand behavior of future economic agents – extending the work mentioned above. This will serve as a starting point or reference model for the demand modeling conducted herein. Work that can be upgraded as new information or game-changing technology options become available. The point is to assemble the best model available right now, with the ability to upgrade it as needed.

An Economic Basis for SMR Value

Establishing an economic basis for SMR is a critical enabling step in frontier development. This basis will depend upon defining the nature of users for materials and products created in space. Customers and their preferences can be modeled, predicted and, indeed, even directed. This is the bread and butter of market research, marketing, and advertising. Preferences for customers in space will follow natural consumption patterns as humans do what they have always done: create, consume, play and expand. Each of these elements can contribute to the creation and expansion of economic value. A market-based vision for moving upward into the next frontier in a sustainable fashion will map the demand side of future economic value. Models about the nature & behavior of emerging and potential markets in space can quantify future consumption when supply and price are used to solve for equilibrium conditions. The basis for human consumption in space can be projected from terrestrial patterns, and will be a function of location, logistics and cost. This enables a link between present human demand, preferences and consumption patterns to be made for the decisions of future economic agents; thereby, enabling demographic, preference and other rich data sources to be used to model future market behavior in space.

In general, the higher the price of imports, the higher the value of local production. Models of direct consumption, as well as likely technical substitutions, will define which future SMR scenarios are viable and where latent SMR value may lie (for example ice at the lunar cold traps). Bold new ideas and concepts are steadily migrating toward a quantitative basis for predicting space demand patterns based upon per-capita usage of SMR. By quantifying supply and demand using the language of economics and finance, investors with real capital can begin to position and even engage in early frontier development.

> *"As the saying goes, what gets measured is what gets done. As leaders think about realizing and capturing the full value of economically disruptive technologies, this idea might serve as a call to action."* [Manyika, 2013]

On the production or supply side, an understanding of how the mining and energy industries work, from a mathematical perspective, can illuminate future opportunities and help predict the value of SMR composition, timing and location. Plenty of relevant analogies are available, yet technical arguments for modification to microgravity and vacuum conditions will be required. A rich and detailed literature on supply-side economic and technical analyses exists for mine production and manufacturing. Blending the expertise of industrial, mining and civil engineering with aerospace engineering is a good place to start.

Likelihood of Market Demand

Asteroid platinum-group metals (PGMs) and base metals have high market certainty if they are sold as terrestrial commodities; but, would suffer from much lower prices than those associated with in-space destinations (as well as volume or throughput limits - small increases in market volume can cause prices to collapse – a common problem faced by today's mining industry). In comparison, space-based products (for example propellants derived from asteroid or Moon/Mars water) have high market uncertainty (no customers exist to date), yet prices are expected to increase as a function of distance (more specifically, transportation energy) from Earth's surface. For the purpose of this evaluation, modeling of terrestrial markets can be done simply by examining current price and quantity information from existing exchanges. Customers are 100% certain to purchase returned space commodities at or below the market price. The results can be directly used for feasibility analysis, and are often misused to justify very large asteroid valuations (typically this is when market size limits are ignored). While the process is straightforward, economic analyses to date have produced no indications of SMR value sufficient to justify return to market (e.g. see RAP work above).

Space markets are more problematic. They suffer from lower certainty. This is the 'if you build it, the customer will appear' problem often faced by new products and technologies. However, the increase in value of three orders of magnitude or more (e.g. the price of water on ISS vs. Earth) could easily overcome this market credibility gap.

> *"After precious metals, it doesn't seem like water would be such a hot commodity. But the company believes it's just as important, as it can be broken down and used to develop rocket fuel. In fact, that same 500-meter-wide asteroid "contains 80 times more water than the largest supertanker could carry and could provide… If the water were converted to rocket propellant, [the asteroid would produce] more than 200 times the rocket fuel required to launch all the rockets ever launched in human history.""*[Fritz, 2012]

Due to its novelty and importance in the aerospace business world, a quantitative *in-space SMR market* modeling approach will be developed in more detail below. Likelihood will be used to weight the contribution of uncertain future markets to present value. This will enable discounting of the time value of money and cumulative market risk. The basic insights needed to build market likelihood functions are already in place. Low-value, high probability markets are easy to model and understand. They have a wide range of existing customers. Most-likely markets (e.g. lunar or asteroid derived propellant or space solar power) have been discussed in the SMR literature for some time; and, they serve as the primary basis for modeling SMR value. High-value, low probability markets are especially interesting, and may offer nonlinear paybacks (or certain ruin) to early investors. Examples of this include a hypothetical macro-scale lunar cold trap Bose-Einstein Condensate (BEC) manufacturing facility or a commercial lunar neutrino observatory. Linkages to other markets, enabling infrastructure and requirements for full market manifestation, also offer an interesting set of questions to be answered.

6.3 In-Space Market Demand Based on Human Tourism & Settlement

Clear goals regarding tourism and human settlements on Mars are emerging from a growing number of high-net-worth individuals. The leadership of PayPal billionaire Elon Musk in this effort is indeed forging a credible path to the red planet for future settlers and supporting commercial enterprises.

> *"In his Heinlein prize acceptance speech, he said he wants to put 10,000 people on Mars. Musk rarely makes public statements merely for effect but a call for 10,000 would-be Martians is extraordinary, even by his standards. When I query him on this point, he pauses. Is he reconsidering? Yes... but, as with so much else about Musk, not in a predictable way. "Ultimately we don't really want 10,000 people on Mars," he says, after letting the pause linger a few seconds more. "We want millions.""* [Klerkx, 2011]

Translating the technical requirements for human space settlement into a credible and feasible vision for a 'deep space economy' can begin with modeling future space commerce based upon the ultimate consumer: a future space colonist. This per-capita approach offers a point of departure that can then be decomposed into technical, financial and policy goals, milestones and objectives. Rich sets of data on human consumption patterns and preferences can be found in marketing literature. Demographic analyses of future space settlers and tourists has been underway for many years. Markets in space will evolve in a similar path to markets on Earth, constrained by environment and physics, yet rich with new opportunities. The same basic drivers: consumer needs or desires, the existence of support infrastructure, emerging extraction or manufacturing technologies, and the creation of transportation and logistics networks, can help predict whether a commercial concept will thrive or die on the vine. These elements can be approximated in order to glimpse how future markets in space are likely to work and support each other. Beginning with the assumption of a future demand scenario, the engineering design and costing phase for meeting that demand can proceed, enabling convergence on whether that demand can be met in a profitable fashion (also known as feasibility), completing one iteration or turn of the model.

Translating Architecture and Operations into Consumption and Cost

The technical requirements for space transportation and life support are well-understood. This enables the fabrication of a logistics and supply chain model to meet the projected demand and consumption patterns of future space settlers. Human space development will eventually include space infrastructure, colonies, settlements, stations, and mining and processing operations. Each of these functions have analogies on Earth, making modeling a straightforward process of remapping into a new physics. By linking those models together to bound regions of technical and economic feasibility, a bigger picture can emerge regarding which development paths for future space settlements are reasonable within a given time frame.

SMR Supply Functions

The technical basis for extraction and supply of SMR-derived products into a future space economy has been studied for many years. Lunar in-situ resource utilization (or ISRU) systems have been modeled by NASA, and are now in the stage of prototype hardware development and testing. Adapting these designs for use on Mars or asteroids has also begun on a conceptual and experimental basis. Costing of conceptual hardware and operations can leverage the experience of prior NASA programs and missions [see Blair, 2002]. The operations and cost models can then be aggregated into SMR production or supply functions, estimating unit costs for various space-derived products.

A valuable 'background reference' for estimating the future performance and cost of space infrastructure elements lies within the engineering, cost and operations experience of NASA. The existence of a large-scale human spaceflight organization with sufficient transparency to understand how it operates, makes decisions and bundles subsystems into complex functional capabilities is also enabling as it allows us to apply lessons learned to private space settlement. Open information on the NASA budget, large-scale systems integration and programmatic experience can serve as an important measuring stick against which to measure or estimate the effectiveness and even efficiency of private space investment.

6.3.1 Primary Ground Rules and Assumptions

Primary Strawman model assumptions are related to the energy 'cost' of space access (the so-called 'delta-V', or change in velocity), the daily and annual quantity of human water use (for both consumption and transportation), the location of transportation and consumption nodes, the cost and productivity of asteroid mining equipment, and the price of terrestrial competition.

> *"Ground rules and assumptions include both internal and external circumstances or events that are believed likely to happen. They describe the major decisions and the economic environment that affects the cost estimate. Ground rules and assumptions are based on the operation, maintenance and support of the system. Ground rules and assumptions generally include: the O&M period, base year of dollars, type of dollars, inflation indices, costs to be included or excluded, guidance on how to interpret the estimate properly, and clarification to the limit and scope in relation to acquisition milestones."* [NASA, 2008]

Delta-V Assumptions

The most important variable influencing future propellant use is the energy 'cost' of space access, typically reported as change in velocity, or delta-V, in the aerospace industry. Because the SMR Strawman model estimates per-capita water consumption for space settlers, and because electrolyzed water is the most efficient chemical propellant currently known, these delta-Vs are a critical parameter in the modeling effort.

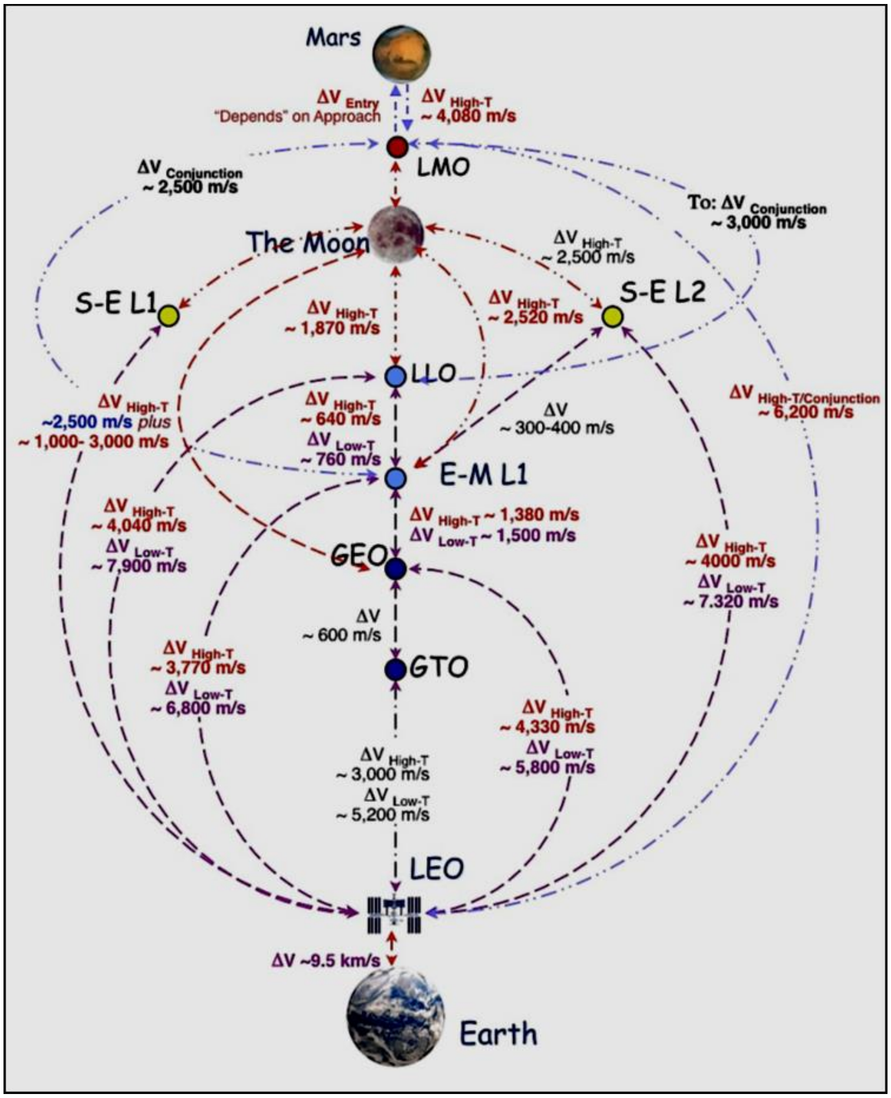
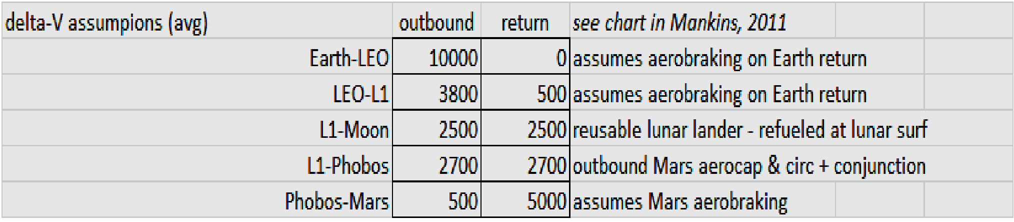


Figure 6-6, Delta-Vs in Earth's Neighborhood [Mankins, 2012].

For the SMR Strawman model, the following approximations (shown in Table 6-1 below) will be used to calculate outbound and return propellant mass. All delta-Vs are assumed to be constant. In other words, individual missions are assumed to pursue the most efficient (or least energetically costly) transportation route available. For this reason, the propellant masses estimated for the Strawman are considered to provide a lower-bound on future consumption (i.e. this is a minimum value - actual propellant use could be higher at the discretion of the customer).



delta-V assumpions (avg)	outbound	return	*see chart in Mankins, 2011*
Earth-LEO	10000	0	assumes aerobraking on Earth return
LEO-L1	3800	500	assumes aerobraking on Earth return
L1-Moon	2500	2500	reusable lunar lander - refueled at lunar surf
L1-Phobos	2700	2700	outbound Mars aerocap & circ + conjunction
Phobos-Mars	500	5000	assumes Mars aerobraking

Table 6-1, Delta-Vs in the SMR Model Forecasting Propellant Usage.

Implementation of delta-V values will be done by accumulating and bundling payload mass and then estimating the amount of propellant needed to push payloads from node to node in a deliberately simplified transportation network. This could enable later optimization using transportation network flow modeling, cost minimization, or throughput maximization methods and software.

For certain asteroids, the Delta V to return payload to a stable orbit in the Earth-Moon system (i.e. proximal to customers) from the asteroid could be less than to enter and escape from the Moon's gravity well. Although many of these low-energy transfer opportunities may have a long waiting period. Under these conditions water from asteroids could present a competitive advantage over lunar water. Both sources offer an absolute advantage over water from the Earth in terms of the physics of mass transfer given current transportation technology for customers in space. Translating advantageous physics into an economic opportunity, however, requires the right alignment of technology, cost and markets.

Technical Ground Rules and Assumptions

A number of other imbedded technical and simplifying assumptions will be helpful in constructing a demand model that is transparent and understandable to both technical and non-technical audiences. A short summary of technical assumptions includes:

- Water will be utilized for both propellant & life support for growing space settlements on the Moon, Mars, Phobos and asteroids
- Water is the propellant of choice – no other alternatives are modeled (derivatives such as kerosene and peroxide are possible to model; but, substitution will add complexity and mass while reducing efficiency thus increasing propellant quantity and a lower bound on consumption)

- Reusable in-space transportation systems are assumed, with dry mass estimated at a constant 15% of wet mass (i.e. individual systems will self-optimize to this level)
- Hydrogen / liquid oxygen are assumed as propellant of choice for all transportation
- Propellant conversion from water to H2/LOX at ~6:1 ratio (near stoichiometric engines could improve efficiency – wasting less oxygen – as translated into water demand, this correlates to roughly 80% conversion efficiency)
- Chemical transportation will be used from 2010 through 2025 (Isp = 460sec)
- Nuclear thermal or solar thermal engines will be used from 2026-2070 (Isp = 1800sec)
- Imported industrial equipment mass will scale directly with people (who are the source of industrial demand); and, grow with time as a ratio per person
- Showers are important - later colonists will want more than drinking water (call this a luxury substitution)
- Closed loop systems will eventually recycle water (implemented as an efficiency ratio)
- The rocket equation can be used to convert passenger mass (fully burdened) to propellant requirements on a per-capita basis (explained below)
- Fully burdened passenger mass includes food, water, equipment, and a proportional share of SMR and industrial hardware
- Aerobraking is assumed for Mars aerocapture / landing as well as Earth return
- Delta-Vs are derived from Mankins, 2011

All assumption will build on prior assumptions to create a simple and transparent template for problem formulation and the identification of a feasible solution.

Economic Ground Rules and Assumptions

In addition to the list of technical assumptions above, the following economic / financial assumptions are offered. While many of them are not explicitly implemented in the model, their presence is assumed and their inclusion is defended as being bounded within the feasibility space of the model results. Economic modeling Ground Rules and Assumptions include:

- The period and start date of operations is 2010-2070
- The types of dollars used for consistent cost estimates are 2013 $USD
- The inflation rates and discounting assumptions include a WACC of 25%, which includes a base rate of 4% annual inflation, an average cost of equity/debt of 6% and a bundled, but non-specified, risk premium of 15%
- The frequency or model granularity is set at 15 year intervals for point estimates, with an assumed discreet linear annual interpolation for cumulative value calculations
- Planetary cruise, orbit insertion/encounter, entry, descent, and landing (EDL), surface operations, extended operations and disposal are assumed but not designed
- Operations concepts for deployment, routine operations, servicing/logistics operations, and disposal are assumed but not designed
- For human-rated space and planetary surface outposts: launch and assembly, mature operations, phase-out operations and disposal are assumed but not designed
- Operations are multi-mission (e.g., facilities costs and operations teams are shared across all missions)
- Cost-sharing arrangements with partners will include both public and private stakeholders
- Commercial, government and non-government organization (NGO) entities will participate in operations and management on an ad-hoc basis
- Responsibility for government oversight will be implemented at level of the sponsoring or launch nations

If this preliminary examination of SMR feasibility provides adequate justification for further research and model development / refinement, the list above can provide guidance on areas needing further expansion and work effort. The list is included as it is a critical part of gaining the confidence of government cost estimators and professionals in business, finance and venture capital.

6.3.2 Per-Capita Consumption and Transportation

The first commodity with strong projected demand in space is water. Water has been shown to exist on the Moon and asteroids in varying conditions and concentrations, including recently discovered high-grade deposits at the lunar poles. The use of water as propellant for cislunar and interplanetary spacecraft has been studied extensively. Quantitative demand for water as propellant will be a function of system throughput; or, a payload is to flow through a transportation network. It is really a secondary demand driven by the primary demand of moving payloads (human, cargo and infrastructure) to a set of desired destinations in the solar system. Forecasting that primary demand (humans and cargo to in-space destinations) will form the basis for space infrastructure forecasts (SIF) which can then be used to solve for propellant demand. The primary basis and fundamental unit for the water demand model is each human tourist or settler. SMR can then be framed as a fundamental part of the support system that provides both transportation and consumables for that individual. By defining SMR use as a function of per-capita in-space customer demand, this enables model scalability of meeting demand as it grows through time.

Inspiration Mars Consumption Model

Requirements for the daily human consumption of oxygen and water have been extensively studied by NASA and a growing number of aerospace contractors. The results of these analyses have been utilized to design life support and extra-vehicular activity (EVA) systems for the U.S. Apollo, Shuttle missions and the International Space Station. Russian and Chinese experience mirrors these results. For the purposes of the simplified SMR Strawman model, a summary of unit human consumption will be derived from the recent work by Dennis Tito and Inspiration Mars [Tito 2013a and 2013b].

Figure 6-7, Inspiration Mars Architecture, 2018 Flyby [Tito, 2013b].

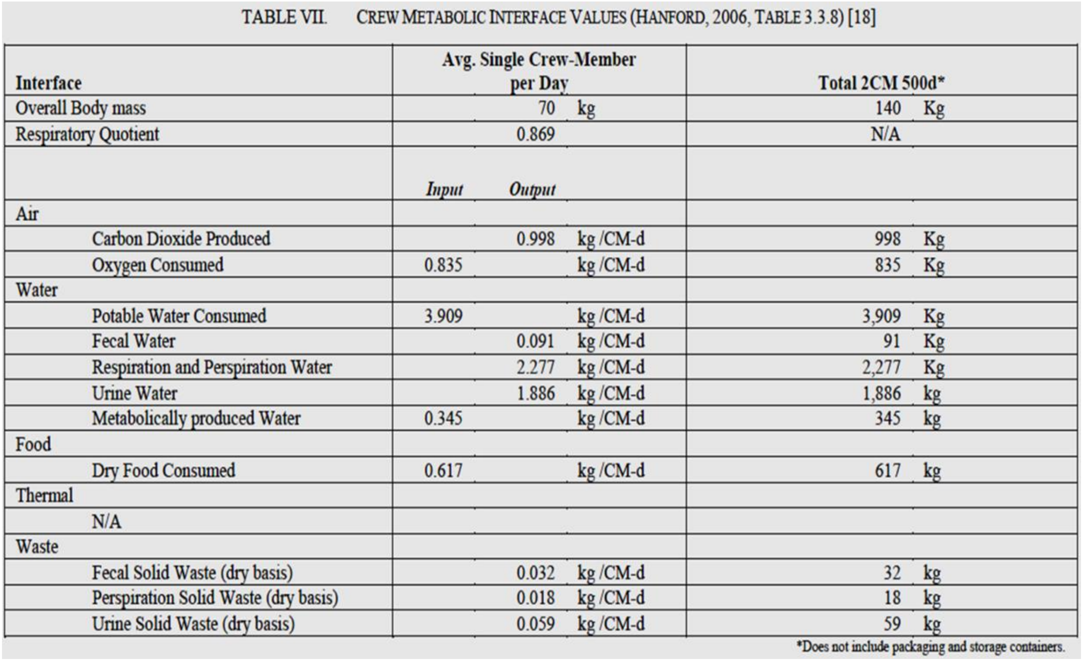


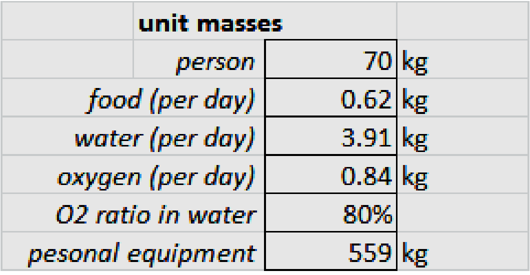
TABLE VII. CREW METABOLIC INTERFACE VALUES (HANFORD, 2006, TABLE 3.3.8) [18]

Interface	Avg. Single Crew-Member per Day			Total 2CM 500d*	
Overall Body mass		70	kg	140	Kg
Respiratory Quotient		0.869		N/A	
	Input	*Output*			
Air					
Carbon Dioxide Produced		0.998	kg /CM-d	998	Kg
Oxygen Consumed	0.835		kg /CM-d	835	Kg
Water					
Potable Water Consumed	3.909		kg /CM-d	3,909	Kg
Fecal Water		0.091	kg /CM-d	91	Kg
Respiration and Perspiration Water		2.277	kg /CM-d	2,277	Kg
Urine Water		1.886	kg /CM-d	1,886	kg
Metabolically produced Water	0.345		kg /CM-d	345	kg
Food					
Dry Food Consumed	0.617		kg /CM-d	617	kg
Thermal					
N/A					
Waste					
Fecal Solid Waste (dry basis)		0.032	kg /CM-d	32	kg
Perspiration Solid Waste (dry basis)		0.018	kg /CM-d	18	kg
Urine Solid Waste (dry basis)		0.059	kg /CM-d	59	kg

*Does not include packaging and storage containers.

Table 6-2, Inspiration Mars Model - Metabolic Needs [Tito, 2013a].

The table above and other inputs from the same report were condensed and simplified to create the version shown in the table below, which forms the primary basis for calculating outbound and return payload mass for sending humans to solar system destination such as the Moon and Mars.



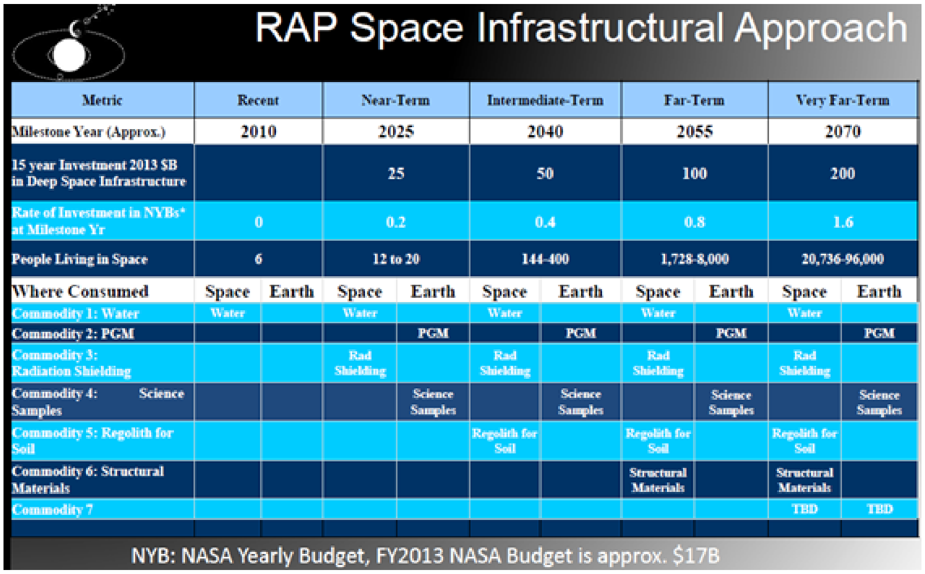
	unit masses	
person	70	kg
food (per day)	0.62	kg
water (per day)	3.91	kg
oxygen (per day)	0.84	kg
O2 ratio in water	80%	
pesonal equipment	559	kg

Table 6-3, Simplified Human Consumption Model [after Tito, 2013a].

Having arrived at a per-capita daily consumption, it becomes possible to estimate annual consumption and, more importantly, the *propellant demand* needed to take human explorers to their destination of choice. But first, the destinations need to be defined and the number of travelers determined.

6.4 Space Infrastructure Forecast (SIF)

Infrastructure will be required for humans living and working in space. Estimating outbound payload (the human settler + their incremental share of support equipment and consumables) on a per-capita basis allows a simple way to build a rational and defensible demand estimate based upon a key variable of interest – the number of human settlers. This approach is the core of the SMR Strawman business case analysis. In this century, space settlement infrastructure could support from hundreds to thousands of people on the Moon, Mars and NEOs. A basic space infrastructure network is quantitatively modeled, positing transportation nodes, tourists and settlers at various destinations between Earth orbit, the Moon and Mars. This is a first iteration of what will become a forecast for the growth of human support infrastructure through time. The first-order estimate will be based upon the NIAC-RAP work (see Table 6-4 below). It will target the Mars population goal of 10,000 settlers stated by SpaceX founder Elon Musk as a goal within his lifetime.



RAP Space Infrastructural Approach

Metric	Recent		Near-Term		Intermediate-Term		Far-Term		Very Far-Term	
Milestone Year (Approx.)	2010		2025		2040		2055		2070	
15 year Investment 2013 $B in Deep Space Infrastructure			25		50		100		200	
Rate of Investment in NYBs* at Milestone Yr	0		0.2		0.4		0.8		1.6	
People Living in Space	6		12 to 20		144-400		1,728-8,000		20,736-96,000	
Where Consumed	Space	Earth	Space	Earth	Space	Earth	Space	Earth	Space	Earth
Commodity 1: Water	Water		Water		Water		Water		Water	
Commodity 2: PGM				PGM		PGM		PGM		PGM
Commodity 3: Radiation Shielding			Rad Shielding		Rad Shielding		Rad Shielding		Rad Shielding	
Commodity 4: Science Samples				Science Samples		Science Samples		Science Samples		Science Samples
Commodity 5: Regolith for Soil					Regolith for Soil		Regolith for Soil		Regolith for Soil	
Commodity 6: Structural Materials							Structural Materials		Structural Materials	
Commodity 7									TBD	TBD

NYB: NASA Yearly Budget, FY2013 NASA Budget is approx. $17B

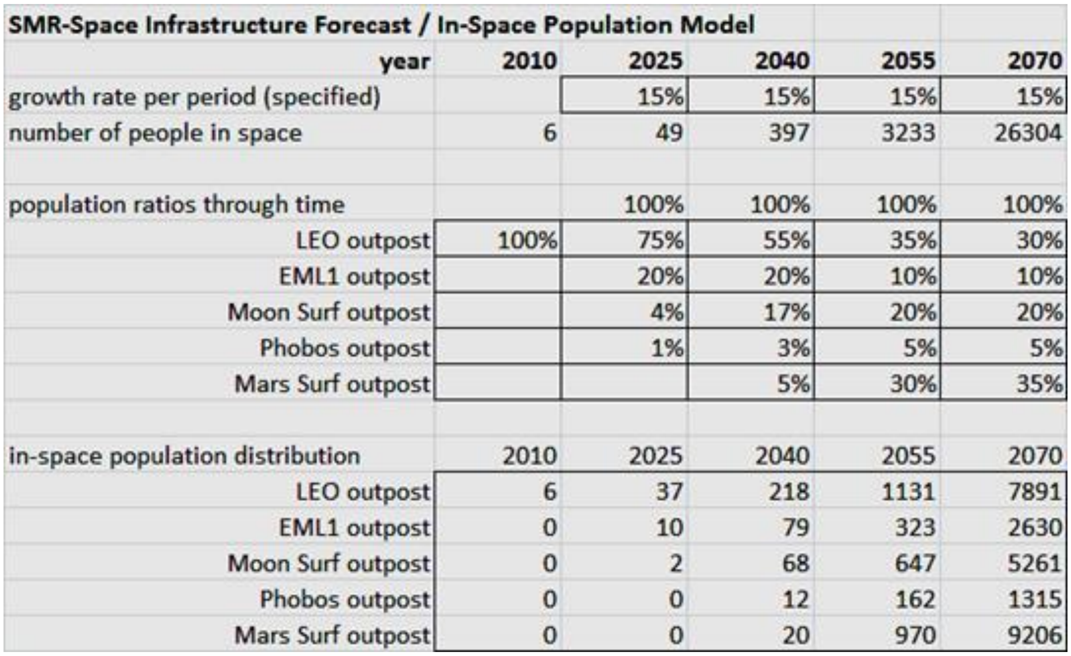
Table 6-4 RAP Space Infrastructure Approach [Cohen, 2013b].

Number of People Living in Space

A critical variable in developing the SIF model is the projected number of people living continuously in space (reported in 15-year increments to match the RAP model above, although 10 year increments would certainly make calculations and results simpler to understand). This population forms the basis or source of demand for modeled commodities, consumables, and future products produced and delivered in space. The estimates herein assume there will be a given number of berths within a reusable transportation network that will be continuously occupied by cargo, crew members, tourists or migrants. Some will chose to rotate back to the Earth at the end of their journey. The assumed start year for the model is 2010, roughly corresponding to the date six people began living continuously on the ISS. Growth projections for the RAP model use the following equation (Note: this model is exponential, yielding a great big number or GBN in the 11th period - year 2160):

$$\boxed{Year2 = \frac{(Year1)^2}{2^{period}}, so, \frac{6^2}{2^1} = 18 \text{ people living continuously in space in } 2025}$$

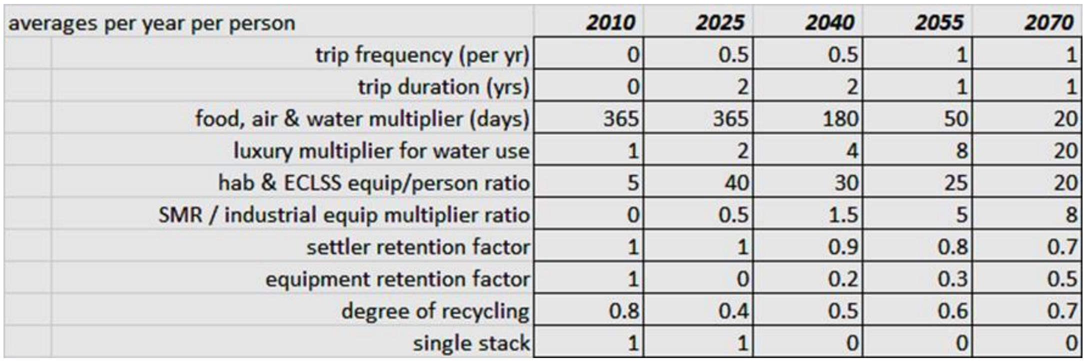
Instead, the SMR-SIF assumes a constant annual growth rate of 15% per year. This leads to a steady increase in later periods that mirrors boom town growth rates; and is, therefore, sustainable from the perspective of the availability of a steady supply of immigrants. Another important assumption is the increasing use of SMR progressively enabling 'independence' from terrestrial constraints - which could lead to autogenous settlement growth (ignored in the current Strawman – however, this could be modeled by increasing consumables without the associated transportation propellants). Finally, an assumption is made that simple ratios could capture the distribution of tourists and settlers through various nodes and destinations. The result of the above assumptions is shown below in Table 6-5 – the population forecast subset of the SIF.



SMR-Space Infrastructure Forecast / In-Space Population Model					
year	2010	2025	2040	2055	2070
growth rate per period (specified)		15%	15%	15%	15%
number of people in space	6	49	397	3233	26304
population ratios through time		100%	100%	100%	100%
LEO outpost	100%	75%	55%	35%	30%
EML1 outpost		20%	20%	10%	10%
Moon Surf outpost		4%	17%	20%	20%
Phobos outpost		1%	3%	5%	5%
Mars Surf outpost			5%	30%	35%
in-space population distribution	2010	2025	2040	2055	2070
LEO outpost	6	37	218	1131	7891
EML1 outpost	0	10	79	323	2630
Moon Surf outpost	0	2	68	647	5261
Phobos outpost	0	0	12	162	1315
Mars Surf outpost	0	0	20	970	9206

Table 6-5, SIF Population Forecast

This approach is deliberately oversimplified and is intended to provide the larger framework to conceptualize the deep space infrastructure. It serves as a foundation for estimating the imbedded human economy that will demand products and services. Indeed, it could even serve as a point of departure for scaling engineering and technology requirements in order to serve that future potential human population. It could also serve as a useful baseline to examine the value of upgrades in technology or capability. Combining a population forecast with consumption and payload assumptions in order to calculate propellant requirements requires a nested set of assumptions. These variables can be set to satisfy the preferences or beliefs of various investigators.

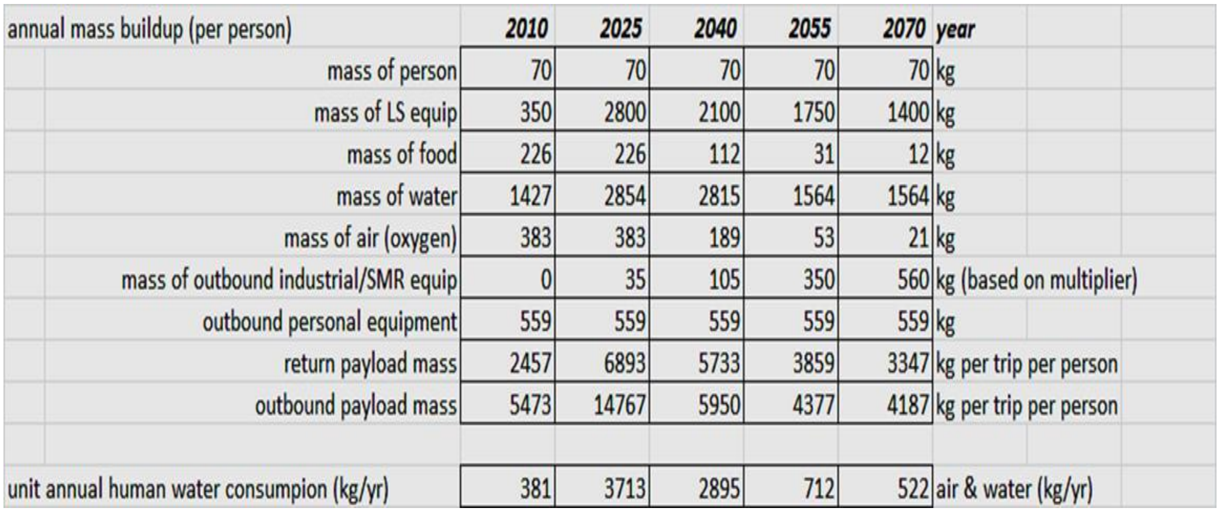


averages per year per person	*2010*	*2025*	*2040*	*2055*	*2070*
trip frequency (per yr)	0	0.5	0.5	1	1
trip duration (yrs)	0	2	2	1	1
food, air & water multiplier (days)	365	365	180	50	20
luxury multiplier for water use	1	2	4	8	20
hab & ECLSS equip/person ratio	5	40	30	25	20
SMR / industrial equip multiplier ratio	0	0.5	1.5	5	8
settler retention factor	1	1	0.9	0.8	0.7
equipment retention factor	1	0	0.2	0.3	0.5
degree of recycling	0.8	0.4	0.5	0.6	0.7
single stack	1	1	0	0	0

Table 6-6, Primary SMR-SIF Variables

A description of the primary model inputs shown in Table 6-6 above is as follows. Travel frequency (trips per year) is a weighted average across all destinations and is the number of times per year each member of the population moves through the network (note the greater number of LEO and lunar tourists relative to Mars). The larger numbers for the out years are rationalized for Mars by the inclusion of high-thrust (1800sec Isp) technology for rapid transits in 2055 and 2070. Trip duration (in years) is averaged across all travelers. The food, air & water multiplier (days per year) reflects how many days of food and air supply is needed per year in order to survive for the trip duration. The "maturity" of local food, air & water production technology is assumed to offset this. A luxury multiplier for water use is intended to reflect extra water needed for showers, hot tubs, etc., as customer tolerance for primitive conditions is reduced through time. The habitat & Environmental Control and Life Support System (ECLSS) equipment per person ratio is an estimated relative proportion of habitat and life support mass allocated per person based upon current ISS and Mars mission designs and implemented as a multiplier on the mass of a person. Note that the spacecraft bus or propulsion module is considered as a separate line item. The SMR / industrial equipment multiplier ratio is implemented as an outbound per person multiplier effect, with equipment shipped outbound to the final destination (e.g. Mars surface) but not back to Earth. Tourists are treated similarly, with a settler retention factor or tourist to settler ratio used to estimate how many folks need to be transported back home per year as a ratio of the forecast. The equipment retention factor is related – it is the ratio of personal effects that get left at the final destination (such as EVA suits, specialty tools, etc.). The degree of recycling (this also includes % annual losses) is the amount of water and oxygen that gets recycled onsite – not needing replacement as a consumable. Finally, the single stack multiplier couples return payload to the outbound spacecraft (e.g. the Apollo mission architecture) for earlier trips to the Moon and Mars, reflecting early exploration and pre-SMR implementation.

The assumptions above combine with the unit human consumption shown in Table 6-7 to provide the following annual consumption buildup mass estimates. These values will then need to be transported to the various destinations.



annual mass buildup (per person)	2010	2025	2040	2055	2070	year
mass of person	70	70	70	70	70	kg
mass of LS equip	350	2800	2100	1750	1400	kg
mass of food	226	226	112	31	12	kg
mass of water	1427	2854	2815	1564	1564	kg
mass of air (oxygen)	383	383	189	53	21	kg
mass of outbound industrial/SMR equip	0	35	105	350	560	kg (based on multiplier)
outbound personal equipment	559	559	559	559	559	kg
return payload mass	2457	6893	5733	3859	3347	kg per trip per person
outbound payload mass	5473	14767	5950	4377	4187	kg per trip per person
unit annual human water consumpion (kg/yr)	381	3713	2895	712	522	air & water (kg/yr)

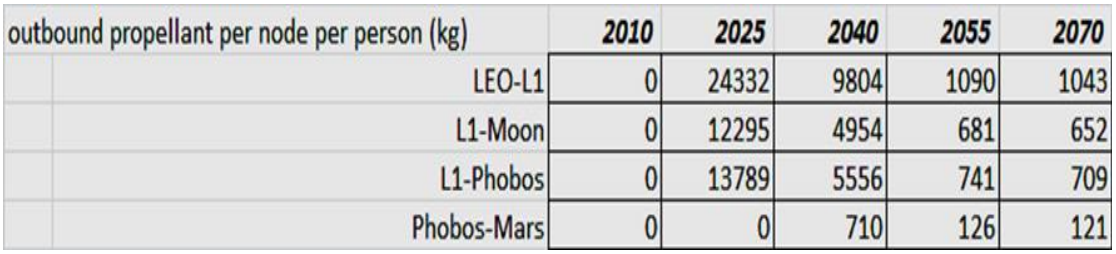
Table 6-7 Aggregate Consumption per year.

The basic summation for mass buildup per consumer or traveler starts with mass of person + personal effects + proportional share of habitat and life support equipment + food + water + air (oxygen). This actually defines minimum return payload mass (which is modified downward for equipment left behind) because it is the minimum mass needed to get someone back home safely. Adding outbound industrial (SMR + mfg) equipment then return payload mass (for single stack payloads) defines outbound payload mass. This becomes the basis for unit annual human consumption in kg/yr. The next step will be to estimate transportation requirements in order to solve for the needed propellant demand level per period.

6.5 Product Distribution and Refueling Nodes

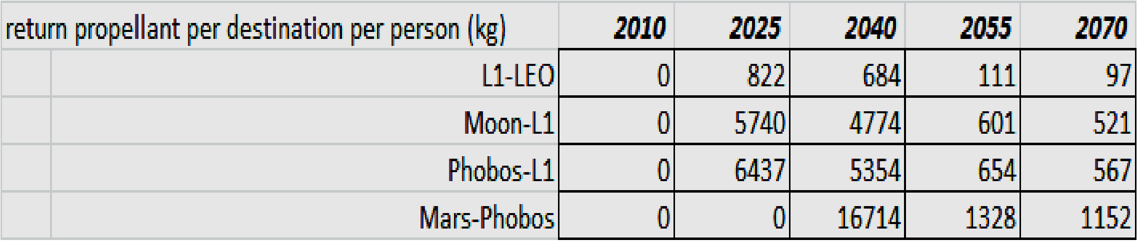
Production of water will happen at the space resource; and, it will then be delivered to a transportation node for distribution to refueling customers. Production will be handled next. This section presents the distribution and refueling assumptions. The approach uses simplifying assumptions to make the model independent of transport system details (i.e. the need to pick a launch provider, design space architectures and transfer stages, etc.) by using per-capita outbound and return metrics. The rocket equation can become iteration-free by assuming a constant 15% basis for bus mass as percent of total mass. Assuming this would remain constant with a change in transportation technology - e.g. the substitution of ion, solar, fusion or fission rockets – makes it possible to model the effects of a higher specific impulse system without substantially disturbing other assumptions. While this may not be realistic, it is considered conservative in that it creates a lower bound on propellant demand.

Propellant distribution, refueling and resupply nodes are assumed to be progressively deployed and maintained by commercial entities at LEO, EML-1 (but could be any Earth-Moon Lagrangian point), Phobos, Mars and Earth's Moon. The spacing of these nodes in roughly equal increments of delta-V (in the range of 2-4km/s) enables the use of reusable transportation systems across the network, provided aerobrakes and landing legs are available when needed. Low-Earth orbit (LEO) is assumed to be a destination as well as a transport and refueling node for all outbound traffic. It is assumed that the EML-1 depot serves both outbound Moon and Mars traffic and inbound traffic from the same destinations for Earth return. A lunar surface depot would serve Moon - EML-1 traffic including propellant shipments, crew and cargo. The Mars surface depot would serve outbound Mars / Phobos traffic, including propellant, cargo and returning tourists and crew. For the purposes of simplicity, low-Mars orbit (LMO) is considered to be the equivalent of Phobos orbit. The Phobos node and depot would serve all inbound EML-1 / Mars surface traffic as well as outbound Earth return traffic. This flow network is deliberately oversimplified for the purposes of transparency and can easily be made more sophisticated at the expense of clarity. Simulating traffic using monte-carlo methods would be an excellent way to add valuable details to results. Pushing outbound and return payload mass estimated in Table 6-8 using these stacking assumptions (and as modified by the multipliers in Table 6-9) yields the following outbound and return propellant requirements.



outbound propellant per node per person (kg)		2010	2025	2040	2055	2070
	LEO-L1	0	24332	9804	1090	1043
	L1-Moon	0	12295	4954	681	652
	L1-Phobos	0	13789	5556	741	709
	Phobos-Mars	0	0	710	126	121

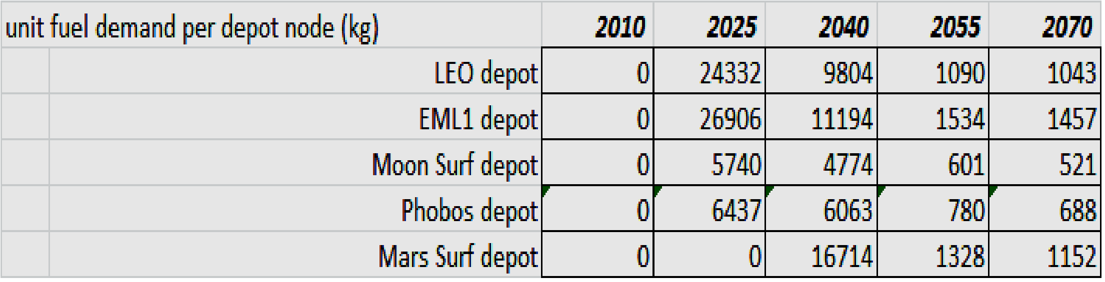
Table 6-8 Outbound Propellant per Person.



return propellant per destination per person (kg)	2010	2025	2040	2055	2070
L1-LEO	0	822	684	111	97
Moon-L1	0	5740	4774	601	521
Phobos-L1	0	6437	5354	654	567
Mars-Phobos	0	0	16714	1328	1152

Table 6-9, Return propellant per person.

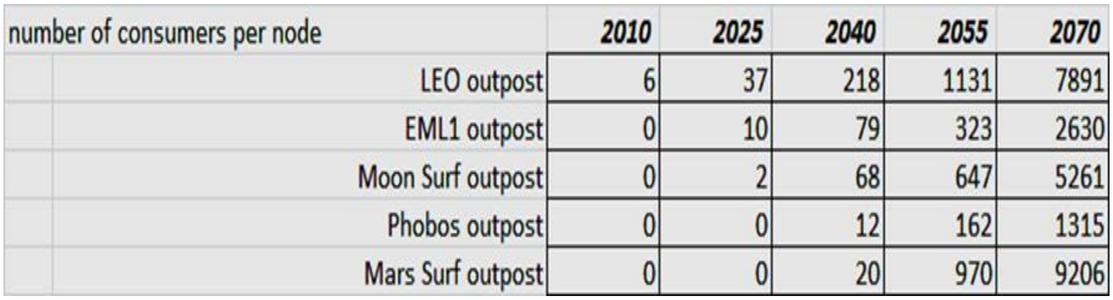
Outbound and return propellant are then combined to yield annual unit fuel demand per person per node as shown in Table 6-10 below. Note that these are point estimates for the year of the interval. Interpolation can be used to estimate annual propellant needs between interval years, and will be used for cumulative economic results in the summary section.



unit fuel demand per depot node (kg)	2010	2025	2040	2055	2070
LEO depot	0	24332	9804	1090	1043
EML1 depot	0	26906	11194	1534	1457
Moon Surf depot	0	5740	4774	601	521
Phobos depot	0	6437	6063	780	688
Mars Surf depot	0	0	16714	1328	1152

Table 6-10, Total Propellant per Person at each Interval Year.

The next step is to combine the population model derived in Table 6-5 earlier and summarized in Table 6-11 below in order to generate throughput – needed to estimate propellant usage.

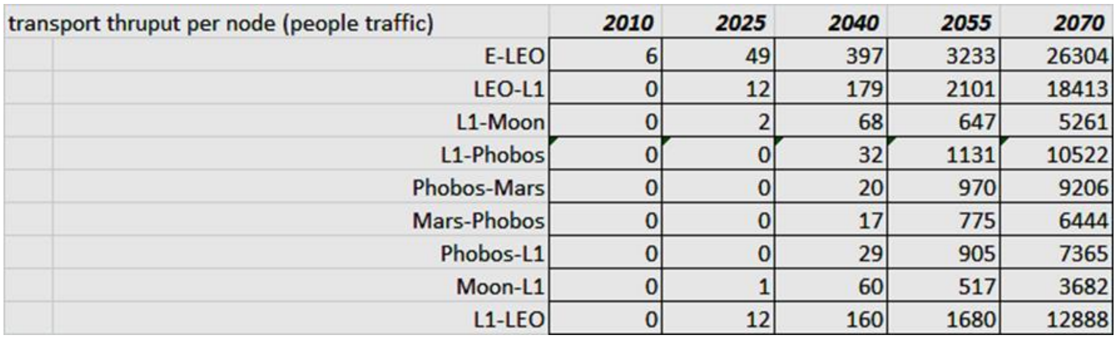


number of consumers per node	2010	2025	2040	2055	2070
LEO outpost	6	37	218	1131	7891
EML1 outpost	0	10	79	323	2630
Moon Surf outpost	0	2	68	647	5261
Phobos outpost	0	0	12	162	1315
Mars Surf outpost	0	0	20	970	9206

Table 6-11, # of Consumers per Node (population forecast above).

Multiplying the number of consumers by their unit fuel demand will yield total consumption; however, there are both forward and counterblows happening. Note that Phobos has a two-way flow and

EML-1 has a three-way flow. The point estimate of passenger throughput at each interval year specifies and accumulates movement in each direction. This transportation network is very simplified compared to what is likely to evolve. This simplifies the modeling at the expense of fidelity. Easy enough to upgrade for future work.



transport thruput per node (people traffic)	**2010**	**2025**	**2040**	**2055**	**2070**
E-LEO	6	49	397	3233	26304
LEO-L1	0	12	179	2101	18413
L1-Moon	0	2	68	647	5261
L1-Phobos	0	0	32	1131	10522
Phobos-Mars	0	0	20	970	9206
Mars-Phobos	0	0	17	775	6444
Phobos-L1	0	0	29	905	7365
Moon-L1	0	1	60	517	3682
L1-LEO	0	12	160	1680	12888

Table 6-12, Throughput – # of Travelers through each Node.

The following bat chart illustrates node location and flows of settlers and infrastructure in the simplified Earth-Moon-Mars system.

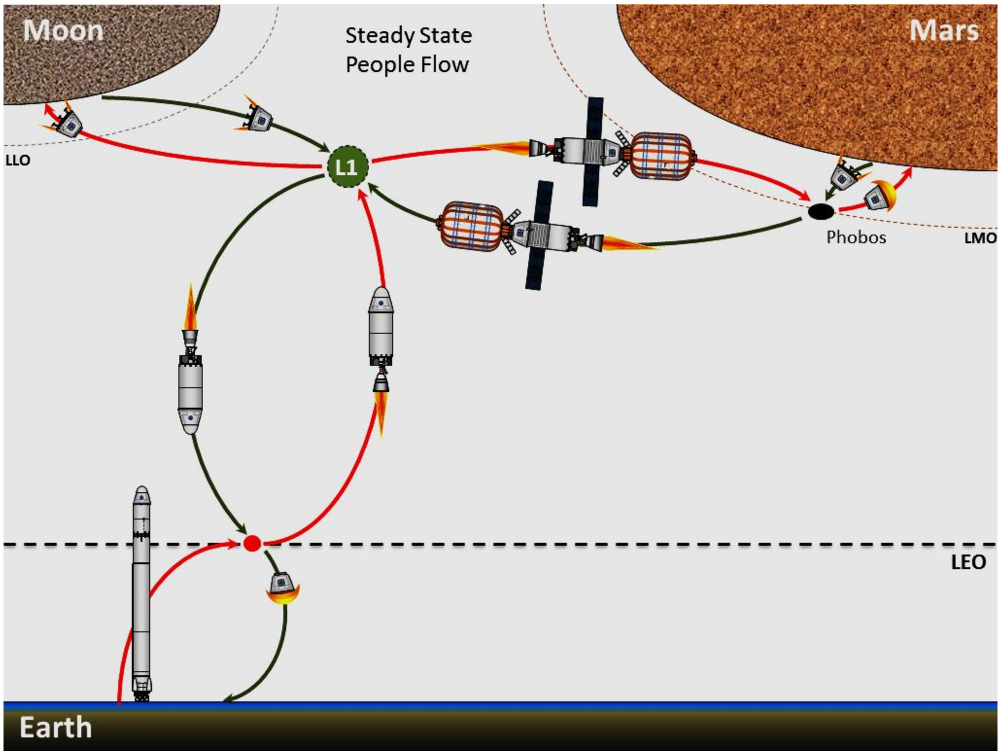
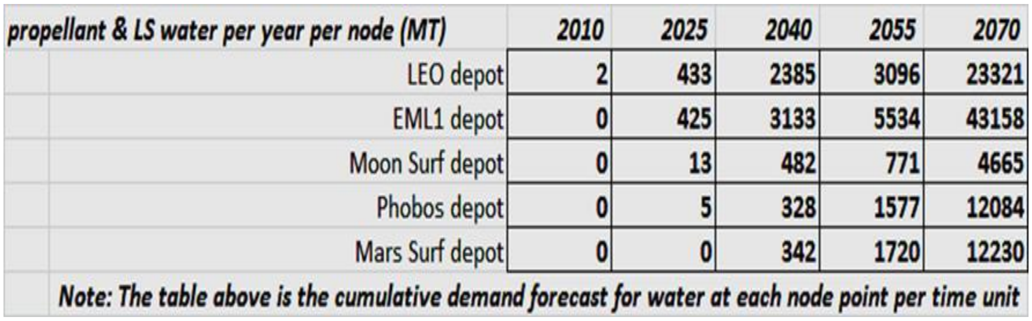


Figure 6-8, Bat Chart Steady-state Flow Space Settlers and Tourists.

The final piece is calculation of the combined tonnage of propellant and life support consumables by multiplying the flow of travelers through each node by their individual or unit consumption & transportation needs. Traffic unit consumption = annual water demand at each node. Results are shown below in Table 6-13.



propellant & LS water per year per node (MT)	*2010*	*2025*	*2040*	*2055*	*2070*
LEO depot	2	433	2385	3096	23321
EML1 depot	0	425	3133	5534	43158
Moon Surf depot	0	13	482	771	4665
Phobos depot	0	5	328	1577	12084
Mars Surf depot	0	0	342	1720	12230

Note: The table above is the cumulative demand forecast for water at each node point per time unit

Table 6-13, Total Estimated Propellant per Node.

The results of these analyses show that the propellant needs are maximized in out years at the EML-1 depot at over 40 thousand metric tons per year. Not surprising as it is the hub with the most human throughput. The big surprise is the quantity needed at Mars' surface for return flights. Commercial asteroid mining companies should pay attention to these results – they will frame their long-term business cases.

Finally, the assumption that water will be the propellant of choice for future human space settlement transportation is deemed to be conservative. Other propellant choices such as kerosene could be made using CO/CO^{2} from asteroids or frozen at the lunar poles. The process would be less efficient, consume more energy and provide less propulsion thrust. In short, the water demand numbers represent a minimum amount of propellant throughput for a SMR supplied transportation network. Other propellant choices would be more massive and would actually increase annual tonnage – not reduce it.

6.6 SMR Strawman Concept of Operations

Combining the SIF and Propellant Demand Nodes model developed above with the RAP architecture yields a simplified yet workable concept of operations (or ConOps) for an economic feasibility analysis. It explains how to deliver water to EML-1 while delivering mission and product unit cost estimates. Yet several elements are missing. These include propellant production at the surface of the Moon, Mars and Phobos, as well as propellant at LEO. The integrated Strawman ConOps model is shown in the bat chart below. It assumes propellant production and distribution systems at each node shown in the chart as well as modeled above. A future commercial operator is assumed a charge of a flat 25% premium on the base cost of water delivery for their services, at each node. As a significant amount of electrical energy is required to convert water into hydrogen and liquid oxygen, this may, indeed, underestimate a depot operator's cost function. Further analyses of the need for electrical power in space could yield an important data set for promoters of Space Solar Power, an important non-mineral space resource.

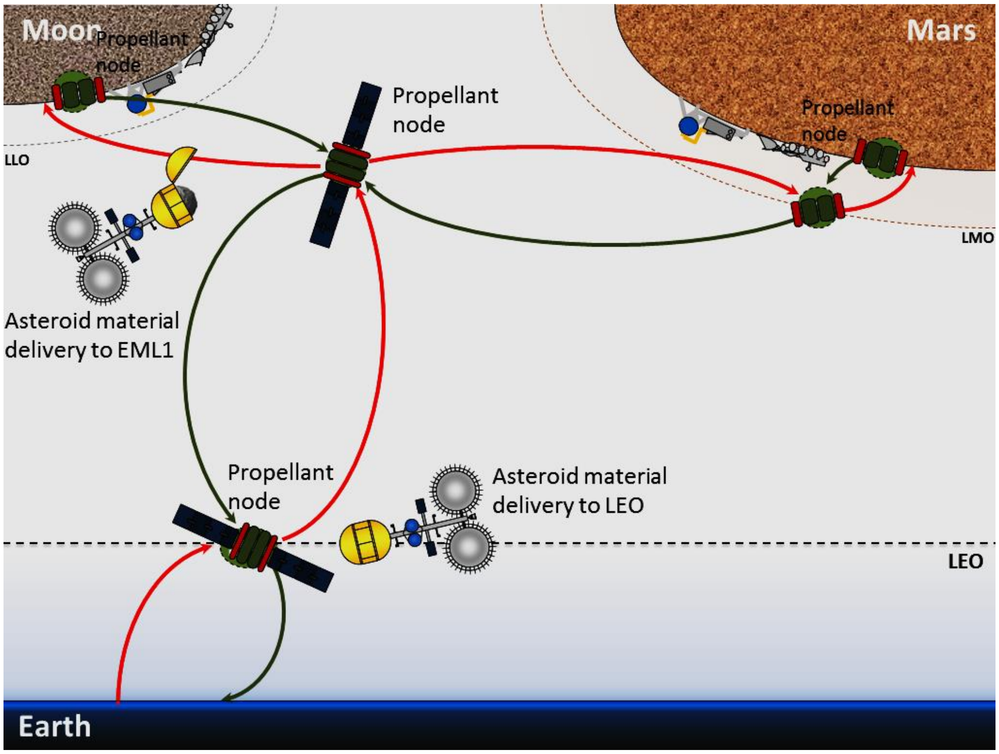


Figure 6-9, Strawman ConOps for location of Propellant Nodes

The development of asteroid mining system engineering details (at subsystem and component levels), as well as validation of cost models, is one area that needs a lot more work. A high degree of uncertainty rests on unchecked RAP model assumptions. Still, it is the highest detail design available to date.

6.7 SMR Price and Equilibrium Modeling

Moving forward requires an in-space water pricing policy that scales with distance from Earth. Price is viewed by economists as the intersection of a buyers 'willingness to pay' and a sellers 'willingness to accept' payment. It can be viewed as an equilibrium process; a communication or negotiation resulting in an agreement to participate in an economic transaction. Price is very different than cost. Indeed, the difference between them can yield either profit or loss. The maximum value of in-space commodity prices will be set by competition. For early SMR, this will be terrestrial competition. Commercial space miners will not be able to sell their early products for more than it would cost to supply the same material from Earth. If SMR operators do price above the equivalent cost of Earth launch, it is assumed that a terrestrial competitor would try to fill the need. Later SMR will see the emergence of competition from other operators (e.g. lunar miners trying to beat the prices of asteroid miners at EML-1). In the long-term, the results of in-space competition would benefit the end customer by steadily reducing commodity price. This can be modeled by setting limits based upon anticipated cost plus profit and asymptotically approaching those limits as a function of the total number of competitors. The ability to model enterprise costs as well as price, as a function of destination or supply node location, enables the use of economic theory to construct scenarios for how competition could evolve in space. In the longer-term, this competition will drive the price of space commodities low enough to allow SMR to displace earth industry players for mining and manufactured goods (particularly for dangerous or toxic industries or products).

The RAP architecture assumed an unspecified customer (presumably a propellant depot with its own propellant customers or other water users) at EML-1 would demand 1800 tons over 4 years and be willing to pay nearly $20,000 per kilogram of water. This estimate was based upon published SpaceX price estimates to LEO (well below the industry norms according to their website) combined with a simplified upper stage design and cost estimate.

Industry costs for lunar and Mars access are a bit more challenging to estimate. Yet they clearly exist imbedded within space industry data sets. The challenge is to draw them out. An attempt was made to use a cost-as-percent-of-mass argument as a crude approach to estimate outbound lunar and Mars pricing using both emerging NewSpace data sets and published Mars rover mission data. Astrobotic Technologies (a Google Lunar X-Prize contender) recently released a commercial price list for access to the Moon [Astrobotic, 2013b]. The data are summarized in Table 6-14 below and clearly show what expendable technology does to cost – it makes it exponential.

Astrobotic RFQv3 - July 2013	http://www.astrobotic.com/wp-content	mass-kg	unit cost-k/kg	destination	total cost-$M
Payload delivery to TLI.	Up to 663kg, starting at $99,000/kg	663	99	TLI	65.6
Payload delivery to lunar orbit.	Up to 515kg, starting at $198,000/kg	515	198	LLO	102.0
Payload delivery to lunar surface.	Up to 270kg, starting at $1,200,000/kg	270	1200	LS	324.0
Payload delivery to lunar surface destination on a robotic rover.	Up to 120kg, starting at $2,000,000/kg	120	2000	LSR	240.0

Table 6-14, Commercial Price at Lunar Surface [Astrobotic, 2013b].

Augmenting the list above with published data on the cost of United Launch Alliance's Delta-IV Heavy rocket using its rated payload capacity to LEO, GTO and GEO fills the gap for those orbital destinations [see Wade, 2011]; and, it is consistent with a 'business as usual' approach to launch cost (i.e., no game changes yet). Finally, data derived from a recent NASA's Mars Exploration Rover mission [NASA, 2003] was added to the space access cost-vs-destination model, with an approximation of cost build up matched against actual masses for the all-expendable mission. Table 6-15 below shows the resulting estimated cost model for destinations throughout the Earth-Moon-Mars system. While this approximation is relatively crude (and easily upgraded with better data), its simplicity has value in creating a maximum price model for valuing SMR in the face of projected terrestrial competition. The right most column (modified unit cost) reflects a uniform "1/3 of actual cost discount" (implemented as the discount ratio seen below) meant to account for the cost efficiency of new commercial operators as lead by SpaceX.

					discount ratio	0.33333
source	mass-kg	total cost-$M	unit cost-k/kg	destination		**Modified unit cost ($k/kg)**
Delta IV-H	27569	254	9.2	LEO		**3.1**
Delta IV-H	12999	254	19.5	GTO		**6.5**
Delta IV-H	6365	254	39.9	GEO/L1		**13.3**
Astrobotic price list	663	65.6	99.0	TLI	TLI stage payload	**33.0**
Astrobotic price list	515	102.0	198.0	LLO	LLO payload	**66.0**
Astrobotic price list	270	324	1200.0	LS	lander payload	**400.0**
Astrobotic price list	120	240	2000.0	LSR	rover payload	**666.7**
MER rovers unit cost est	6000	60	10.0	EL		**3.3**
MER rovers unit cost est	1062	110	103.6	TMI	TLI stage payload	**34.5**
MER rovers unit cost est	827	190	229.7	LMO	aeroshell payload	**76.6**
MER rovers unit cost est	174	320	1839.1	MS	lander payload	**613.0**
MER rovers unit cost est	50	350	7000.0	MSR	rover payload	**2333.3**

Table 6-15, Projected Price to Moon/Mars showing 1/3 Discount Ratio.

The data above clearly shows the exponential nature of the price of space access that results from the current combination of systems expendability and exponential stacking needed for interplanetary missions. Figures 6-10 below plots the costs above in linear and log format. Notice how well the data line up on the log chart. The 1/3 discounted numbers will serve as the basis for SMR pricing in early years and serve as a proxy for the anticipated NewSpace price structure. Note that exponential price increases as a function of distance is the *core rationale for the SMR business case*. This underscores the very real economic argument to use local resources for propellant supply, enabling significant efficiency due to the reuse of capital assets by refueling rather than discarding them after a single use.

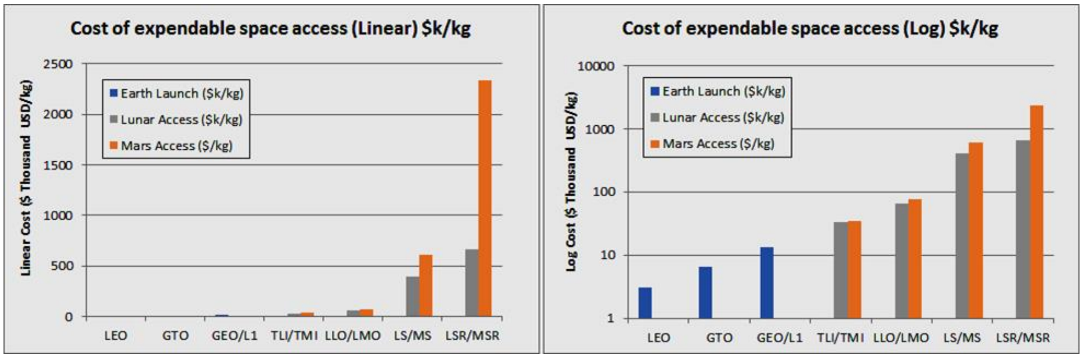


Figure 6-10, Projected Price to Moon/Mars, Linear and Log Format.

6.8 Strawman Analysis and Evaluation

Systems analysis and evaluation of the Strawman business model yields an important set of conclusions. First and foremost is the observation that EML-1 and the lunar surface dominate early recoverable economic value for SMR (remember that EML-1 is supplied by asteroid resources). This is not a surprising result; and, it is not actually based upon the Moon's resources. It is based upon the value of both locations (in addition to LEO) as a destination for human settlement.

Expanding the Strawman Model for Other Products

Future market scenarios can bound values for products beyond water. If a production function can be built that decomposes product mining and refining into a series of technical inputs which include mass and power estimates per unit of product (e.g. reducing Martian iron oxide to make steel products), the basis is formed to translate between technical and economic terms. The use of steel on Mars would enable fabrication of a wide variety of industrial and consumer products as well as infrastructure. By creating demand scenarios with parameters rated in terms of space settlers, a tie-in is created to the SIF, easily extending its utility. A simple way to distinguish prices for different commodities or products is to estimate the added value, or energy, in its production. Note that purity is a major factor in mined and refined products on Earth; and, it has a significant premium associated with high-purity elements. Another proxy for cost is product complexity or discerning need vs. wants (a luxury premium approach).

The market likelihood approach offered above is another way to model some of the more outlandish ideas by using a very low weight for likelihood. It is noted that adding two to three orders of magnitude to price is possible with many space resources sold in space markets vs. Earth markets; but, the likelihood of individual scenarios would be lower (usually not by three orders of magnitude – and this is the point that illuminates SMR value in space). Space products that have been widely discussed in the press include Rare-Earth Elements (REEs), Platinum-Group Metals (PGMs) and base metals (Al, Fe, Mg, Ni, Co, Ti). For the Moon, it may be possible to utilize purified Calcium or Potassium as a conductor for power applications. These metals would immediately oxidize in Earth's environment and are, therefore, not used. Other substitutions may be enabled in unique space environments.

> *"Rare-Earth elements are not an economic option. Although the initial RAP proposal included REEs as a potential option, there is*

> *not economically advantageous basis for returning REEs from Space to the Earth. REEs on Earth are not rare at all; rather the economics of producing them have favored cheap labor and high tolerance of environmental degradation, which has given China a near monopoly. New, environmentally safe processing technologies can make REEs much more widely available, although perhaps not less expensive."* [Cohen, 2013b]

While very attractive in terms of current price (yet limited by terrestrial market size), platinum group metals (PGMs) for return to Earth may prove to be a diversion from the main future market for asteroid materials: Water customers who will be located in space. It is possible that in-space demand could arise for PGMs, REEs, and other exotic elements or materials for in-space industrial use. However, by themselves, these scenarios are not strong enough to form a baseline economic case for SMR. With water paying for the infrastructure, platinum group metals, and even base metals, could make sense as byproducts of water production. In many terrestrial mines, byproduct production is typically where profits for mining companies are earned. The main product keeps the mine open and pays the bills – the byproducts produce economic profit.

As long as mining costs are covered, returning platinum from asteroids could accelerate the adoption of fuel cell technology by lowering price and expanding supply. Due to their unique and valuable properties (including non-oxidation), PGMs are among the most prized industrial metals known to man. They are part of a bundle of materials and technology that could ignite a space industrial revolution. Base metals would further accelerate this revolution by providing a feedstock for building gigantic structures in space.

6.9 Summary

Sustainable development of solar system resources requires identifying profitable conditions for lunar, Mars, or asteroid mining. An integrated technical-economic approach is a useful tool for identifying and bounding feasible regions for future private investment in space resources.

An analytical assessment process will be useful for determining whether specific asteroid mining business cases are viable. This is ultimately based upon the existence of a credible market (in addition to credible cost strategies and supply functions). Modeling tools have been used to create a set of point estimates that define an economically feasible region for a SMR Strawman systems architecture in market, cost and technical terms. Technical and architectural parameters were used to generate a systems-level supply function, which drove the cost model, using a concept of operations and a customer forecast. A separate demand function was created using a projected in-space product and customers at various locations. Equilibrium point estimates resulted from mapping supply to demand and illuminating a feasible solution. Note that this solution would normally attract commercial investment under terrestrial conditions and risk preferences (i.e. if its nature as a market opportunity in space were obfuscated).

The industrial use of SMR is no longer science fiction; and, its feasibility is no longer entirely an engineering function – the game changer is becoming policy, law & economics. Preliminary economic conclusions include (1) architectures based upon returning precious metals to terrestrial markets alone appear to be non-starters, (2) the existence of in-space customers for propellants, consumables, structural materials or shielding could make asteroid mining economically feasible under the Strawman assumptions and conditions, and (3) longer-term hybrid architectures with both terrestrial and in-space customers could become feasible as costs drop and market size increases.

It is an important SMR conclusion that the high cost of space access from Earth directly contributes to economic profitability. In other words, maintaining high Earth to orbit launch costs is enabling for SMR. While it is clear that SpaceX is developing a credible path to lowering launch costs, there may be a negative incentive to rapidly drop prices to their new cost level should stimulating the space economy be in their long-term interest. In this situation, the generation of large profits is very likely which would accelerate movement of needed capital in the direction of space enterprises.

Investors or government agencies who wait for complete information run the risk of missing the boat. By definition, emerging market opportunities never have full information and remain in the category of high risk investments. Should high ROI be indicated in models, sufficient risk capital could become available to further refine model inputs, later exploiting real opportunities. Reducing perceived and actual risk is a well understood process in industry.

> *"Investors who wait too long risk missing out." … "History shows that when investors are at their most pessimistic on emerging markets, a strong buying opportunity is created."* [Titherington, 2013]

There is clearly a business case for water mining once settlers arrive. The question becomes one of whether the infrastructure can be built to support a human migration to space. The answer will engage architecture studies, business modeling and the search for and development of technology breakthroughs, especially in space mining, refining, manufacturing and repair.

This whole chapter has been structured around a launch vehicle (chemical rocket) infrastructure to escape Earth's gravity. One can only image the change across the whole financial projections when the space elevator is executed and changes the cost to orbit from $10,000 per pound to LEO to an estimated $100 per pound. In addition, there are going to be advances in electric propulsion and nuclear thermal rockets that will make the movement inside our solar system so much easier and more economical.

Chapter Seven, SMR Policy, Legal, & Considerations

7.0 Introduction:

There have been many recent discussions on this topic in many conferences as more and more people are looking to support space mineral resource projects. Philip Harris, in his article "Space Law and Space Resources,"[5] summarized well with:

> "The official position of the United States clearly enunciated in the debates of UNCOPUOS, interprets these provisions to permit any nation or corporation to mine and otherwise use the resources of outer space…… Even under the rather anticapitalistic Moon Treaty, the official position of the U.S. negotiators in UNCOPUOS has been that the treaty permitted companies and nations to mine the Moon. For instance, light elements hydrogen, nitrogen, and carbon-exist in limited quantities in the lunar soil, and frozen water may exist in larger amounts at the lunar poles. Under the longstanding U.S. legal interpretation, the nation finding these resources will be able to mine them. The nation will not own the site, but its labor will attach ownership to the ore."

This chapter will address the present policy issues and treaties in place that deal with SMR activities. However, we must also consider the lessons of history. Ralph Cordiner[6] started thinking about this many years ago and noted some questions that are still relevant today.

- *"How can we utilize our dynamic system of competitive private enterprise in space, as on earth, to make newly discovered resources useful to man?"*

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[5] Phillip R. Harris, *Space Law and Space Resources*, *in Space Resources vol. 4, Social Concerns*, (NASA-California Space Institute, 1992) *available at* http://www.nss.org/settlement/nasa/spaceresvol4/spacelaw.html.

[6] Ralph Cordiner, *Competitive Private Enterprise in Space, in Peacetime Uses of Outer Space*, 213-140 (Simon Ramo ed. 1961).

- *"How can private enterprise and private capital make their maximum contribution?"*
- *"What projects will necessarily require government chairmanship and support for their execution?"*
- *"What must be done to preserve a free society while competing in an international race for space?"*
- *"How can we assure that when the space frontier is developed, it will be an area of freedom rather than regimentation?"* [Cordiner, 1961]

Yet it is not history that will define the landscape, but the actions of decision makers and influencers in the here and now that are most relevant. The SMR industry is finally emerging from a long winter of regulatory frost and chilling inaction. Governments are now moving from quiet support of SMR activities to open and deliberate cultivation of the industry. It is in this spring thaw that we see the blooming of policies and practices that will finally cement the legitimacy of private SMR activities.

As the realization of private SMR harvesting continues to draw near, its legality continues to progress thanks to the support, however small or specifically directed, of the US Federal Aviation Administration (FAA) and other nations. George Nield (Associate Administrator of FAA) stated "We're not talking about property rights at this point… What we're talking about is having the U.S. government have a regulatory framework that provides some certainty so they will be free to proceed with their plans and raising of funds."[Foust 2015a] Nield said more work was needed on that regulatory framework to ensure the government was able to meet its obligations under accords like the Outer Space Treaty to provide oversight of activities by the private sector.[Foust 2015b] "The FAA's decision 'doesn't mean that there's ownership of the moon,' Bigelow stated. 'It just means that somebody else isn't licensed to land on top of you or land on top of where exploration and prospecting activities are going on, which may be quite a distance from the lunar station.'" [SpaceKSC, 2015] The FAA's authority is limited to launch licensing and its letter does not directly speak to the legality of SMR harvesting.

7.1 General Policy, Legal and Regulatory Considerations:

Space policy is built around ratified treaties and internationally accepted customs. The written laws that set the stage for exploration and commercial utilization of space consist of four treaties. The first, the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies,* is the dominant law that enables countries and companies to operate within that environment. There will be much discussion on this treaty and how it supports the SMR efforts. The second, *Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space*, third, *Convention on International Liability for Damage Caused by Space Objects*, and the fourth *Convention on Registration of Objects Launched into Outer Space*, are all relevant as they deal with operational issues and will be reviewed quickly.

- The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (the "Outer Space Treaty"), adopted by the General Assembly in its resolution 2222 (XXI), opened for signature on 27 January 1967, entered into force on 10 October 1967;
- The Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space (the "Rescue Agreement"), adopted by the General Assembly in its resolution 2345 (XXII), opened for signature on 22 April 1968, entered into force on 3 December 1968;
- The Convention on International Liability for Damage Caused by Space Objects (the "Liability Convention"), adopted by the General Assembly in its resolution 2777 (XXVI), opened for signature on 29 March 1972, entered into force on 1 September 1972;
- The Convention on Registration of Objects Launched into Outer Space (the "Registration Convention"), adopted by the General Assembly in its resolution 3235 (XXIX), opened for signature on 14 January 1975, entered into force on 15 September 1976.

The Outer Space Treaty, internationally accepted, has been dominant for the last 50 years; but, is only now making its impact upon space faring nations. The Moon Treaty was NOT ratified by any space faring nation except India. As such, the tenants of that failed treaty have been rejected out of hand and are NOT applicable across international space activities, thus not excluding mining on the Moon, asteroids and other bodies in our solar system.

Space Policy: Where Treaty Law Stops, Policy Begins

The policy of most nations is that they will not participate in the United Nations Convention on the Law of the Sea (UNCLOS) or the Moon Treaty (ratified by 60 and 15 nations respectively) as those agreements seek to systematically prohibit the profit motive that so many societies see as their life's blood. The failure of the Moon Treaty is specifically due to the unwillingness of countries to limit their access to the Moon and other celestial bodies—whether for profit, research, or some other yet to be determined purpose; and, many countries have specifically NOT acceded to UNCLOS' International Seabed Authority so as to continue their efforts to mine the seabed (see Steven Groves articles of December 4, 2012 "The US Can Mine the Deep Seabed Without Joining the UN Convention on the Law of the Sea"). This lack of acceptance is equally binding as to its failure.

International Law is also the policy of why countries do not accede to treaties as much as it is due to the treaties they do ratify. The designation of the Moon and other celestial bodies to be "the province of all mankind" does not, in any way, preclude their exploration or exploitation. Recalling the non-appropriation principle of the Outer Space Treaty, it is clear that it is attempting to deny states the ability to claim sovereignty over new territory; thus, allowing for "free access to all areas of celestial bodies" (as described in Article I) is paramount.

The "why not" of signing, or ratifying, the Moon Treaty when the Outer Space Treaty (OST) had been signed, ratified, and in force seems to be specifically based upon Article XI that requires the sharing of resources and profits from the Moon and other celestial bodies. The Moon treaty, however, takes "the province of all mankind" several steps further in Paragraph 3 of Article XI which says:

> "Neither the surface nor the subsurface of the Moon, nor any part thereof or natural resources in place, shall become the property of any state, international intergovernmental or non-governmental organization, national organization or non-governmental entity or of any natural person"

Paragraph 7 of Article XI requires the "equitable sharing by all states parties in the benefits derived from those resources." This is specifically why it is a failed treaty [agreement]. Governments, corporations, and individuals do not wish to be precluded from profiting from space mining! Once again, the policy of most countries is to support commercial development. With that in mind, policy for SMR must be laid out in order to avoid confusion and encourage development across the solar system.

7.1.1 Safety of Near-Earth Operations

A future, internationally accepted, custom could be the cooperative sharing of spacecraft location information around the solar system. Safety (both in a real sense of collision avoidance and as in a proprietary sense of use), is critical to the commercialization of SMRs. A system similar to the Space WARC for de-conflicting placement of NEAs, mining operations, and claims to resources would be a way to build confidence for nations, investors and operators alike. The locations of NEAs, their capture and use, must not become a race for the low hanging fruit; nor should entities be allowed to reserve sites on the Moon, asteroids, or other celestial bodies without a clear intent and ability to proceed. Whether that intent is measured by time, technology, or finances, it should be up to the SMR community itself.

One could even envision a Space Traffic Control Center where interplanetary, Lunar, Lagrangian point, GEO, MEO, and LEO traffic and trajectories could be coordinated and timed to avoid interference. This would have the added benefit of being a clearing house for minimizing delays, blocking maneuvers and space debris creation. All users must be able to detect and avoid others; but, the most maneuverable also has the responsibility to do so. Historical precedent, allowing the first to a point in space to have priority of location (grandfather clause), could be applicable in space also.

Issues on the safety of bringing asteroids into orbit around the Earth, the non-pollution of near Earth space (debris generation, etc.), and requiring Earth safe orbit decay or elevation are all things that will either encourage or block the advancement of SMR activities. Risks can be mitigated with the judicious application of policies, treaties and laws. The more certainty that can be applied to risk criteria, the higher the probability of action, commerce, development, etc. SMR policy, treaty, and legal actions will be particularly enabling or destabilizing.

7.2 Resource Ownership

The current body of international space law, known as the *Corpus Juris Spatialis* (*CJS*), is haunted by a number of ambiguities and issues that have led to confusion and misconception. [7] Of these problems, the largest is the confusion surrounding the use and extraction of the mineral resources of space. This uncertainty has left many pondering

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[7] *See* Bin Cheng, *Studies in International Space Law* 383-424 (1997); Stephen Gorove, *Developments in Space Law Issues and Policies* 18 (1991) (noting that many "vexing problems remain" with the current CJS); Julian Hermida, *Legal Basis for a National Space Legislation* 243 (2004) (commenting on the inadequate mechanisms for private companies to settle disputes under the CJS); Francis Lyall & Paul B. Larsen, *Space Law A Treatise* 42 (2009) ("As a result not all [treaty language in the CJS] is pellucid. . . [Current space activities] were not in contemplation when the space treaties were formulated"); Bryon C. Brittingham, *Does the World Really Need New Space Law*?, 12 Or. Rev. Intl L. 31, 37 (2010) (discussing difficult ambiguity in the CJS); Gennady M. Danilenko, *Outer Space and the Multilateral Treaty Making Process*, 4 High Tech. L.J. 217, 220 (1989) ("Not all the essential subjects amenable to treaty regulation have been resolved. Even during the 'golden age,' states failed to reach agreement on a number of important problems."); Art Dula, *Free Enterprise and the Proposed Moon Treaty*, 2 Hous. J. Int'l L. 3, 8 (1979) ("The Moon Treaty is vague, lengthy, and complex."); Ricky J. Lee, *Reconciling International Space Law With the Commercial Realities of the Twenty First Century*, 4 Sing. J. Int'l & Comp. L. 194, 206 (2000) (commenting on the "present inadequacies" of the current space law regime that has limited the CJS to "vague and abstract terms"); Mark J. Sundahl, *The Duty to Rescue Space Tourists and Return Private Spacecraft*, 35 J. Space L. 163 (2009) (noting and suggesting remedies for the deficiencies in the current rescue and return rules or persons and objects in space); Robert A. Ramey, *Armed Conflict on the Final Frontier: the Law of War in Space*, 48 A.F. L. Rev. 1, 74-100 (2000) (discussing and lamenting holes and ambiguities in the present CJS); Jefferson H. Weaver, *Illusion or Reality? State Sovereignty in Outer Space*, 10 B.U. Int'l L.J. 203, 218-232 (1992) (discussing ambiguities in the CJS which, purposeful or not, are causing present difficulties); Brian Wessel, *The Rule of Law in Outer Space: the Effects of Treaties and Nonbinding Agreements on International Space Law*, 35 Hasting Int'l & Comp. L. Rev. 289, 301 (2012) (Discussing current trends for states to continually reinterpret language within the CJS which is disruptive to the proper rule of law); Julie A. Jiru, *Star Wars and Space Malls: When the Paint Chips off a Treaty's Golden Handcuffs*, 42 S. Tex. L. Rev. 155 (2000) (claiming ambiguities in the OST greatly stymie commercial efforts) ; Lynn M. Fountain, *Creating Momentum in Space: Ending the Paralysis Produced by the Common Heritage of Mankind Doctrine*, 35 Conn. L. Rev. 1753 (2003) (noting the specific provisions and schools of thought within the CJS are "antithetical to the economic development of space resources."); Philip De Man, *The Exploitation of Outer Space and Celestial Bodies - A Functional Solution to the Natural Resource Challenge* (Leuven Centre for Global Governance Stud. Working Paper No. 50, 2010).

the legality of privately harvesting the mineral bounty of space, and whether or not it can even be harvested legally by anyone. Fortunately, a proper and thorough analysis will inevitably conclude that space resources may be freely harvested and that sovereign nations are not prevented from exercising the inherent powers of governance over their own constituents and affairs. Below is an exploration of the formal and customary relevant law, the issues and controversies surrounding the law, and the resolution of those issues.

7.2.1 Legal Background

The *CJS* had its first major development with the creation of the United Nations Committee on the Peaceful Uses of Outer Space (hereinafter COPUOS) in 1958.[8] Realizing that space law inherently invokes issues of international scope, the U.N. General Assembly created COPUOS as an international forum to consider and discuss the emerging issues in space law.[9] COPUOS has seventy-seven member states, and it has facilitated nearly all major space agreements.[10] COPUOS was a key player in the development of the *CJS*,[11] and is still relevant today. However, the topic of space law is becoming increasingly contentious as

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[8] *International Co-operation in the Peaceful Uses of Outer Space*, G.A. Res. 1472 at ¶ A-8, U.N. GAOR, 14th Sess., U.N. Doc. RES 1472 (XIV) (Dec. 12, 1959), *available at* http://www.unoosa.org/oosa/en/SpaceLaw/gares/html/gares_14_1472.html.

[9] *See Id.*

[10] *United Nations Committee on the Peaceful Uses of Outer Space: History and Overview of Activities*, U.N. Office for Outer Space Affairs, *available at* http://www.unoosa.org/oosa/en/COPUOS/cop_overview.html.

[11] COPUOS spearheaded the passage of five United Nations General Assembly Resolutions that greatly helped shape the future of the CJS. *See Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space*, G.A. Res. 1962, U.N. Doc. A/RES/1962(XVIII) (Dec. 13, 1963); *Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting*, G.A. Res 37/92, U.N. Doc. A/RES/37/92 (Dec 10, 1982); *Principles Relating to Remote Sensing of the Earth from Space*, G.A. Res. 41/65, U.N. Doc. A/RES/41/65 (Dec. 3, 1986); *Principles Relevant to the Use of Nuclear Power Sources in Outer Space*, G.A. Res. 47/68, U.N. Doc. A/RES/47/68 (Dec. 14, 1992); *Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries*, G.A. Res. 51/122, U.N. Doc. A/RES/51/122 (Dec. 13, 1996).

individual nations seek to develop and expand space law, and its many ambiguities, in different directions thereby increasing tensions.[12]

The *CJS* can be thought of as "all international and national legal rules and principles which govern the exploration and use of outer space by States, international organizations, private persons and companies."[13] Thus, space law itself is generally derived from three sources: international agreement, customary international law, and domestic legislation. Each of these sources will be examined below in turn. Interestingly, space law has also been shaped by analogous comparison with other areas of international law such as the law of the sea and the Antarctic treaties. This borrowing of principles and norms has allowed for a more structured, if not predictive, understanding of developing space law. Such analogous precedents have greatly shaped and informed the interactions of actors within this legal sphere.

7.2.2 Treaties Concerning Space Mineral Resources

The present CJS has been shaped and informed almost entirely by treaty. Treaties comprise the majority of international space law, and as such should be the first point of interest when examining it. Specifically, two treaties are relevant when discussing space mineral resources: the 1967 Outer Space Treaty or OST and the 1979 Moon Treaty[14]. These two treaties provide both confusion and clarity on the subject, and should be addressed and clarified.

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[12] *See Declaration of the First Meeting of the Equatorial Countries*, Dec. 3, 1976, I.T.U. Doc. WARC-BS 81-E (1977) [hereinafter Bogota Declaration]. In the "Bogota Declaration," equatorial countries attempted to assert ownership of geostationary orbits, and they did so by interpreting the CJS to allow the appropriation of orbits. The attempt failed, but remains as an example of how states will seek to interpret legal ambiguities in their favor.

[13] Peter Malanczuk, *Space Law as a Branch of International Law*, 1994 NETH. Y.B. INT'L L. 143, 147 (1995).

[14] Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, G.A. Res. 34/68, U.N. Doc. A/34/664 (1979) (entered into force July 11, 1984) [hereinafter Moon Treaty].

The field is new enough, and so potentially mutable that customary international law has been unable to form around any but the simplest and most obvious of legal concepts.[15] Thus, while customary international law certainly influences the CJS, the first step should be an examination of existing treaty law. Because of this, it will be important to briefly cover the fundamentals of treaty interpretation. The Vienna Convention on the Law of Treaties (hereinafter Vienna Convention) is the prime source in the interpretation of treaties.[16, 17] In its most basic form, the Vienna Convention declares that "a State is obliged to refrain from acts which would defeat the object and purpose of a treaty,"[18] and that "every treaty in force is binding upon the parties to it and must be performed by them in good faith."[19] In short, each state is to perform its duties under a treaty in good faith. However, issues can arise when parties disagree on the meaning and purpose behind a treaty. The Vienna Convention also provides a framework for sorting out such disagreements.[20] In the event that the rules of the Vienna Convention

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[15] Ramey, *supra* note 7, at 73; Though CIL certainly exists, and has long existed, within the *CJS*, the majority of its principles have been derived though practices established by treaty with the exception of basic principles such as human rights and the laws of warfare.

[16] Many nations have signed the convention, and some such as the United States have not ratified the Vienna Convention, however, its courts have cited to it as CIL. Thus, it binding for most, and at least partially binding for all as domestic law. *See, e.g. Ehrlich v. American Airlines, Inc.*, 360, F.3d 366, 373 n.5 (2d Cir. 2004); *See also* Evan Criddle, *The Vienna Convention on the Law of treaties in U.S. Treaty Interpretation*, 44:2 VA. J. INT'L L. 432, 434 (2004) (noting that many state and federal courts have cited the convention as CIL).

[17] The Vienna Convention says that agreements must be between "states," and this definition seems to exclude nations and belligerents which the Restatement does not by explicitly including non-state actors. *See* Vienna Convention on the Law of Treaties art. 2, May 23, 1969, 1155 U.N.T.S. 331; But cf. Restatement (Third) of Foreign Relations Law § 102 cmt. f (1987) [hereinafter Vienna Convention].

[18] Vienna Convention, *supra* note 17, art. 18.

[19] *Id*. art. 26; This article is often described with the phrase "Pacta Sunt Servanda" which roughly translates to "promises must be kept." *See* Friedrich Kessler, *Pacta Sunt Servanda: A Meditation*, 34 VA. J. INT'L L. 405 (1994).

cannot resolve an ambiguity, the International Court of Justice can be employed by the parties to resolve the issue,[21] or the parties can solve the issue amongst themselves. In practice, situations often occur where a state must interpret a treaty unilaterally, and provided that the interpretation is in good faith and not referred to the International Court of Justice, that interpretation should stand at least for that party.[22]

With a working interpretation established, subsequent practices and agreements, tacit or explicit, will continue to shape the treaty creating the potential for a dynamic definition over time.[23] Finally, international law itself is permissive in nature, if a certain action is not expressly forbidden, literally or by clear implication, it is expressly allowable;[24] the *CJS* is no exception.

The OST as it Relates to Space Mineral Resources

The OST states that space and celestial bodies are free to be explored and used "for the benefit and in the interests of all countries,"[25] that outer space "shall be the province of mankind,"[26] that outer space and celestial bodies are "not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means,"[27] and that "[s]tates party to the treaty shall bear international

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[20] Vienna Convention, *supra* note 17, art. 31, 32; *See Sale v. Hatian Centers Council, Inc.*, 509 U.S. 155 (1993) (applying the Vienna Convention's rules of treaty interpretation, including articles 31 and 32).

[21] Vienna Convention, *supra* note 17, art. 66.

[22] Ramey, *supra* note 7, at 81. This is especially true in space law due to the still evolving nature of the *CJS* and the myriad of definitional interpretive issues. *See generally supra* note 7.

[23] Vienna Convention, *supra* note 17, at art. 31(3).

[24] *See S.S. Lotus (Fr. v. Turk.)*, 1927 P.C.I.J. (Ser. A) No. 10, at 4, 18 (Sept. 7) ("Restrictions upon the independence of States cannot therefore be presumed).

[25] OST, *supra* note **Error! Bookmark not defined.**, art. I.

[26] *Id.*

[27] *Id.*, at art. II. This article, has spawned an immense amount of debate, and its exact meaning is hotly contested.

responsibility for national activities in outer space, including the moon and other celestial bodies."[28] The net effect of these provisions is that some scholars felt this required that the profits or other tangible benefits derived from the commercial use of space or the use of space resources for private purposes should somehow be shared with all nations,[29] regardless of their participation in space activities.[30] Such an obligation, however, does not exist in current law and especially not under the OST. It is sometimes suggested that the OST's prohibition on appropriation prevents the unilateral harvesting of space mineral resources; this is untrue. Outer space is not subject to "national appropriation" by "claim of sovereignty" or "by any other means."[31] This, however, is referring to the claim of new territory, and it profoundly differs from the practice of claiming new territories recognized by international law and practice throughout all human history.[32] It is now

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[28] *Id*., at art. VI.

[29] This has been neither the practice nor precedent set by the international satellite telecommunications industry over the continuing forty years of its existence, itself at present the only mature and profitable business in space.

[30] See Ezra J. Reinstein, *Owning Outer Space*, 20 Nw. J. Int'l L. & Bus. 59 (1999) ("Developing nations argue that it is morally imperative to take the interests of the non-space-capable nations into account when designing a system of space property law. A regime based on the 'right of grab,' the first-come, first-served theory of property acquisition, should be feared. By the time space-incapable nations develop the technological prowess and capital reserves to fund meaningful development of outer space, the earlier space-faring nations, left unchecked, might already have locked up the most accessible and valuable resources. Present inequities of global wealth distribution thus would be carried forward into the space age.")

[31] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, October 10, 1967, art. II, 1967 U.N.T.S. 206 ("Outer space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.").

[32] See *Territory and Boundaries of Nations*, 45 Am. Jur. 2d International Law § 32 (2004) ("When citizens or subjects of one nation, in its name and by its authority or with its assent, take and hold actual, continuous, and useful possession of territory unoccupied by any other government or its citizens, the nation to which they belong may exercise such jurisdiction and for such period as it sees fit over territory so

generally accepted that claiming areas, such as claiming ownership of land on the moon, is against customary international law.[33] Nothing in the OST, however, prohibits commercial use and private ownership of space resources.[34] For example, every State that has engaged in space activity has appropriated space based resources for their own use.[35]

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acquired. While it is possible under principles of international law for individuals to obtain title to territory that they discover, such an occurrence is rare.")

[33] *See* Kelly M. Zullo, *The Need to Clarify the Status of Property Rights in International Space Law*, 90 Geo. L.J. 2413 (2002). "); .*See also* Hongkyun Shin, *Emerging System of Property Rights in the Outer Space*, United Nations / Republic of Korea Workshop on Space Law: United Nations Treaties on Outer Space: Actions at the National Level, 2004, St/Space/22 ("In the absence of a legal definition regarding outer space, the non-appropriation principle is destined for narrower scope and applicability. Article II does not constitute a firm and stable basis for enforcing the non-appropriation rules in member States' domestic law. As the ownership issue, including the legal status with respect to a part of outer space is dealt with in the context of domestic law, the right to use has been allowed.")

[34] OST, *supra* note 14, art. III; *See also* Jiru, *supra* note 7, at 16 (quoting Richard D. Cunningham, *Space Commerce and Secured Financing -- New Frontiers for the U.C.C.*, 40 Bus. Law. 803, 805 (1985) [emphasis added] ("Article III provides that the 'exploration and use of outer space … shall be the province of all mankind [and]… shall be free for exploration and use by all States … on a basis of equality. The developed nations, especially the United States and Russia, view this prohibiting an exercise of sovereignty over outer space and the celestial bodies within it; *nevertheless, appropriation and exploration of any natural resource which may be found are fair game.* It appears that resources may be exploited, so long as this is done with regard to other nations. This answers fears that the clause connected with allowing exploitation and use "for the benefit … of all countries" prohibit appropriation by one nation of resources found in outer space. *These phrases are accepted internationally as guidelines for space-faring nations to use in the development of their space activities, rather than as strict rules. Also notable is that there is no prohibition on private activities in space.* It is possible that, 'the establishment of a permanent settlement or the carrying out of commercial activities by nationals of a country on a celestial body may constitute national appropriation if the activities take place under the supreme authority of the state.' Article III also states that all activities and exploration shall be in accordance with international law.")); *See also* Dr. Stephan Hobe, *Current and Future Developments of Space Law*, ST/SPACE/28 2, 7-8 (United Nations, 2005)(citing G.A. Res. 122, U.N. GAOR, 51st Sess., Supp. No. 20, U.N. Doc. A/51/590 (1996)) ("The UN General Assembly has adopted a resolution with regard to the interpretation in view of current state practice of this provision [Article 1 paragraph 1 of the Outer Space Treaty]. *And this resolution very clearly indicates that states are in principle free to choose solutions how to distribute the benefits from the exploitation of outer space*

The Moon Treaty and How It Relates to Space Mineral Resources

The 1979 Agreement Governing the Activities of States on the Moon and Other Celestial Bodies[36] is indisputably the most controversial and least influential of the five treaties comprising the *CJS*, and is widely considered to be a failed document.[37] As of this writing, only fifteen states have ratified the treaty, none of which are considered a major space power.[38] The locus of the controversy surrounding the Moon Treaty is that it declared all celestial bodies, excluding the earth, within the solar system to be the "common heritage of mankind" (hereinafter CHM).[39] Borrowing from the original law of the sea treaty,

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resources. It is the state that shall determine the way of cooperation with other states and particularly with developing countries. This may be regretted, particularly from the point of view of developing countries which in the 1960s and 1970s with their numerical majority in the General Assembly as a consequence of the decolonization process did struggle very much for a restructuring of the international economic legal order thus including respective exploitation provisions of the international commons. *But the already mentioned resolution of the UN General Assembly is certainly indicative of current state practice that is not supportive of such widespread sharing of benefits*.") (emphasis added).

[35] *See infra* note 50.

[36] Moon Treaty, *supra* note 15.

[37] Cheng, *supra* note 7, at 161; Dula, *supra* note 7; Ramey, *supra* note 7, at 95.

[38] The United Nations Office for Outer Space Affairs maintains a public listing concerning the status of all major space treaties which is viewable on its website: http://www.unoosa.org/oosatdb/showTreatySignatures.do.

[39] To explain the origin of the concept and controversy, Cheng commented that "From the very beginning, the non-space powers wanted to have a share of the fruits of space exploration and exploitation in the form of scientific knowledge, technology, and in due course other material or pecuniary benefits apart from their desire to ban colonialism from, and the militarization of, outer space and celestial bodies. However, all that they succeeded in achieving, nay, all that they were granted by the space powers, in the all-important 1967 Treaty on Outer Space was to make the whole of outer space, including the moon or celestial bodies, *res extra commercium*, which, while it precludes the space powers from appropriating territorially portions of outer space, the moon or celestial bodies, leaves them free, notwithstanding views to the contrary, nevertheless to appropriate their resources." CHENG, *supra* note 7, at 358. In effect, the non-spacefaring countries sought rents from those who were otherwise in a position to reap the fruits of space for themselves. By imposing the CHM doctrine on the moon and every other "celestial body" in the solar system, The Moon Treaty not only sought to distribute any such profit universally,[s*upra* note 14, at art. XI ¶ 7.] but it did so by proposing an international oversight board [s*upra* note 14, at art. XI ¶ 5.].

the CHM concept was included not only for its rent-seeking qualities but to also help foster the peaceful use of outer space by preventing struggles over resources.[40, 41] While the Moon Treaty has been dormant and ineffectual thus far, it may ultimately help the very things it aimed to prevent. Because the treaty was so vociferously protested and unaccepted, it provided a forum for nations to begin establishing patterns and practices that demonstrated open opposition to many of its concepts, and these displays have undoubtedly helped shape the surrounding international law. Because the Moon Treaty is a non-binding failure, it has relevance only insofar as it helps elucidate several principles regarding the *CJS* as it relates to the harvesting of mineral resources.

7.2.3 Customary International Law Relating to Space Mineral Resources

International agreement forms the main body of international space law, but customary international law (hereinafter CIL) is nearly as important. CIL has long been recognized by many sources, and the International Court of Justice is generally considered the first authority in defining CIL.[42] While CIL specific to space is relatively sparse within the *CJS*, it nonetheless exists and defines certain parameters of acceptable conduct.[43]

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[40] CHENG, *supra* note 7, at 361-80.

[41] However, space is literally infinite in scope, and there is an incalculable amount of useful material within the solar system. By preventing the harvesting of this vast bounty, it seems that such a provision might actually foster conflict over scares resources. That said, some space resources are far easier to reach and early on there is a potential for conflict over the “lower hanging fruit.”

[42] *See* U.N. Charter, June 26, 1945 art. 92, 1 U.N.T.S. 16 (“The Statute of the International Court of Justice is annexed to the Charter of the United Nations, of which it forms an integral part. The main object of the Statute is to organize the composition and the functioning of the Court.”); Statute of the International Court of Justice art. 38(1)(b), 59 Stat. 1059 (1945). States will only appear before the International Court of Justice if they have consented, and with the United States being a party to the above agreements, the Court is decidedly relevant in disputes of CIL.

[43] Ramey, *supra* note 7, at 66-67 (“Yet, what little customary law for space there is has been derived from the activity of very few States.”).

CIL can generally be seen as a horizontal system in which states,[44] as putatively equal sovereigns,[45] come together and through the practices and expectations of the large majority, form a body of law that is binding upon all.[46] Over time, certain norms emerge through practice and expectation with some being binding in only a looser sense, whereas others can achieve a specific status as inviolate or sacrosanct.

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[44] Note, that states, while they are certainly the most visible, are not the only actors that can affect CIL. *See* Restatement (Third) of Foreign Relations Law § 301(1) (1987); Jordan Paust, *Customary International Law: Its Nature, Sources and Status as Law of the United States*, 12 MICH. J. INT'L L. 59, 67 (1990) ("Since each nation-state, indeed each human being, is a participant in both the attitudinal and behavioral aspects of dynamic [CIL], each may initiate a change in such law or, with others, reaffirm its validity); Jordan Paust, *The Complex Nature, Sources and Evidences of Customary Human* Rights, 25 GA. J. INT'L & COMP. L. 147, 158 (1995) ("[I]t is the reality of participation in processes of expectation and practice which allows one to recognize that individuals are not merely objects of [CIL], but are also participants in the creation, shaping, and termination of such law; that patterns of 'domestic' practice are relevant, not merely practice state-to-state or at the international level . . .") (citation omitted) [hereinafter *Customary Human Rights]*; See *also*, Christiana Ochoa, *The Individual and Customary International Law Formation*, 48:1 VA. J. INT'L L. 119 (2007) (discussing the gaps in existing law which creates ambiguity in how individuals affect CIL); Julie Mertus, *Considering Nonstate Actors in the New Millennium: Toward Expanded Participation in Norm Generation and Norm Application*, 32 N.Y.U J. INT'L L. & POL. 537 (2000) (discussing the extent to which non-state actors can impact CIL compared to state actors).

[45] Note that there is some friction here. Legal positivism asserts that the CIL system is almost completely egalitarian and that each state's opinion and actions can affect the law as much as any other's. Contrast that with legal realism which accounts for a state's size, its level of interest in the subject, and other factors to create a view that not all actors are equal in the formation of CIL. This tension is especially present in the *CJS* as only a few nations might be considered space-faring.

[46] *See The Scotia*, 81 U.S. 170, 187 (1871) ("[CIL] rests upon the common consent of civilized communities. It is of force not because it was prescribed by any superior power, but because it has been generally accepted as a rule of conduct."); *Ware v. Hylton*, 3 U.S. 199, 227 (1796) ("The law of nations may be considered of three kinds, to wit, general, conventional, or customary. The first is universal, or established by the general consent of mankind, and binds all nations."); *supra* note 17.

CIL is considered binding upon all parties and its obligations are universal.[47] CIL consists of two elements: general patterns of practice or behavior[48] and general patterns of legal expectations or *Opinio Juris*.[49] If both elements are simultaneously present at the right moment, then it is likely that the behaviors and expectations will merge to form a new rule of CIL.[50] However, exceptions do exist, and CIL can form around specific situations, parties, or even geographical areas.[51, 52]

The first prong of CIL, general patterns of practice or behavior, is generally parsed from the observation of a stable theme of widespread conduct by the whole of relevant actors.[53] Though many sources declared that only states may participate in the formation of these

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[47] *Id*.

48 Consider that Sol, earth's sun, is a "Celestial Body" under the terms of the CJS. The light it casts off is no different from any other resource that exists in space, and nearly all space ventures, public or private, have freely utilized solar power without incident. If it is permissible to take solar power for private use, it is equally permissible to utilize the mineral wealth of space as well. No academic has yet put forth a serious notion that utilizing solar power is illegal, and this long history of use has helped cement and further solidify the custom that the SMR bounty of space may also be freely harvested.

[49] Paust, *supra* note 44 at 61.

[50] *Id*.

[51] At its heart, customary international law is, oddly enough, built upon custom. It stands to reason that relatively similar situations, if customarily handled in different ways, can lend themselves to the development of distinct norms and different rules of CIL. For example, it is entirely possible that some customs may arise regarding the use of Mars' moons, but no such custom may eventually exist for the moons of Saturn.

[52] Additionally, some debate exists over whether or not a "persistent objector" is bound by the emerging CIL that begat such objections. *See* Paust, *supra* note 44 at 64 n.14 (noting strongly that while nations might disagree with a rule of CIL, that they are indisputably bound). Note that it is important to distinguish between objecting to a potential rule of CIL and objecting to an already established rule. In the former case, the dissent is useful to dissuade the norm from forming, whereas the latter is illegal.

[53] OST, *supra* note **Error! Bookmark not defined.**, art. I

norms, a modern trend is the recognition that entities other than states can and always have helped create CIL.[54]

The prong of general patterns of practice is especially important in understanding the CIL within the *CJS*. Increasingly, private actors are working in space, and their choices and actions play an important role in setting the culture of space, and hence the resultant CIL. Non-state actors are not only acting privately, but possibly under the authority of state bodies as well.[55,56] Specifically, domestic laws and other state-based actions can and will greatly color the resulting CIL. What began as a treaty can grow into CIL,[57] and what began as domestic laws of conduct can direct the practices and behaviors of those bound by these domestic laws creating more general patterns of practice and behavior.

The second prong of CIL is *Opinio Juris*, or a general pattern of legal expectation among human kind. *Opinio Juris* should be derived from the most comprehensive base possible, and the intensity, duration, and awareness of such beliefs should be closely examined.[58, 59, 60] The *Opinio*

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[54] NANDASIRI JASENTULIYANA, INTERNATIONAL SPACE LAW AND THE UNITED NATIONS 19 (1999) ("Space law has also made an important contribution to the procedural aspects of international law through its development of the consensus procedure. The [COPUOS] was the first UN body to work by consensus.") (footnote omitted).
[55] For example, NASA recently hired SpaceX to deliver cargo to the international space station, which SpaceX did successfully for the first time on March 3, 2013.

[56] Mertus, *supra* note 44, at 553 ("To some extent, states have reallocated elements of sovereignty to other actors, in particular to international regulatory and supervisory organizations, financial institutions, and other 'money managers.' States now operate within an increasingly dense matrix of transnational interactions involving other states, inter-governmental institutions, multinational corporations, and a whole range of cross-border groups.") (citation omitted).

[57] *See* Vienna Convention, *supra* note 17, at art. 38.

[58] *See* Paust, *Customary International Law: Its Nature, Sources and Status as Law of the United States*, *supra* note 44, at 63-64; *Customary Human Rights*, *supra* note 54, at 151.

[59] Generally, court decisions, U.N. Resolutions, scholarly commentary, legal documents, and actions such as specific recognitions can be seen as evidences of *Opinio Juris*, but never as actual sources. *See generally* Paust, *supra* note 44.

Juris of the *CJS* appears much more diverse than the general patterns of practice, if for no other reason than that anyone can write about the law, but only a select few are in a position to actually reach outer space.[61]

With both prongs of CIL accepted generally, if not universally,[62] a new rule can then emerge.[63] Also among the basic principles of CIL are the rules of interaction between it and treaties. In cases of conflict between ordinary treaty and ordinary CIL, there is a split view as to which should prevail. Some sources consider treaty and CIL to be coequal, and unless

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[60] In investigating proof of customary norms and *Opinio Juris* it is only necessary that normative content be sufficiently defined, and that every aspect need not be fully developed. *See Xuncax v. Gramajo*, 886 F. Supp. 162 (D. Mass. 1995).

[61] While the *Opinio Juris* of the *CJS* might enjoy more diversity, it is still very likely that it will be weighted by those in a position to utilize space because domestic cases and other legal products naturally exist in greater quantity in an environment where the concepts are put into practice as opposed to a non-spacefaring actor's strictly academic environment.

[62] *Customary Human Rights*, *supra* note 44, at 151 ("Despite occasional rhetorical flourish, universality of behavior and unanimity are not required. Patterns of human practice need only be general, not uniform, and patterns of *opinion juris* need only be generally shared.") (citation omitted).

[63] The timeframe for the generation of a new rule of CIL can vary, and some suggest that lengthy requirements are but an artifact of a less connected world wherein it was more difficult to observe general custom. [S*ee* CHENG, *supra* note 7, at 192.]; Some commentators have even gone so far as to suggest that CIL can now be "instant" in its formation, though this is a minority view without much traction. [S*ee Id.*; *But see* Ramey, *supra* note 7*,* at 68-69 (citing the International Court of Justice which declared that the passage of time is a requirement for the formation of CIL).]; Generally, CIL is regarded to form over decades, though legal realists consider environmental factors as a possible accelerant to the process. If CIL forms when both prongs exist simultaneously at a relevant point in time, it stands to reason that the loss of one or both prongs can alter or remove CIL as well. Simply put, "[i]f the patterns of violation become too widespread,[…], one of the primary bases of customary law can be lost. Similarly, if it is no longer generally expected that a norm is legally appropriate or required, the other base of customary law can be lost. When either base is no longer generally extant, there can be no conjoining of general patterns of legal expectation and behavior and, for such a social moment at least, a prior customary law will no longer be operative." [*Customary Human Rights*, *supra* note 44, at 151.

parties agree otherwise, a treaty will supersede a prior inconsistent rule of CIL.[64] Other sources submit that CIL is formed from the general patterns of all mankind, and its universal nature cannot be trumped.[65] These points will become very important within the *CJS* as space is further developed. For example, it is argued that the OST, or portions of it, have become CIL.[66] If this is so, to what degree are these norms violable? How strongly are these norms established, and what is necessary to dissolve or cement them? These questions are extremely pertinent when discussing the mineral resources of space. If private harvesting is illegal, then would be miners face a difficult battle for legitimacy. If private harvesting is proper (as this work demonstrates) then each successive effort will further define and cement the legitimacy of such activities. This is especially important in the early stages of resource development because those early efforts are what set the tone and atmosphere for the resultant legal norms.

7.2.4 Analysis and Explanation of Why Resource Extraction is Permissible

Consider the previous discussion that the rejection of the Moon Treaty was an expression of the current *CJS*. It has been noted that the Moon Treaty did not expand any rights within the *CJS*; it added only restrictions.[67] The private utilization of resources on the moon was only prevented insofar as it would take place under a yet to be established

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[64] Restatement (Third) of Foreign Relations Law § 102, cmt. j (1987) ("Customary law and law made by international agreement have equal authority as international law.").

[65] Generally, the opposing argument is that CIL is formed from a much larger pool of thought and action than any treaty. Because CIL is universal in scope, and it is formed from such a large body, treaties cannot generally supplant CIL. Essentially, it would be unfair to allow a few parties to invalidate a universal rule that the majority had created. That said, some room does exist to argue that parties can place treaties above CIL if it would only affect them. *See also*, *The Amistad*, 40 U.S. 518 (1941) (recognizing that fundamental human rights law under CIL takes precedence over treaties).

[66] CHENG, *supra* note 7, at 229.

[67] Dula, *supra* note 7.

oversight regime. While practical and political realities were expected to functionally frustrate resource extraction,[68] there was no legal bar. Thus, the Moon Treaty recognized that resource extraction was permissible. Its rejection was made on grounds that it impermissibly restricted extant rights to retrieve resources which displays international understanding that resource extraction is permissible. Additionally, the Moon Treaty states that "resources in place" may not be appropriated,[69] which implies that once they are removed they are fairly claimable. Interestingly, both the rejection of the Moon Treaty by the major space powers, and its acceptance by some nations, aids in this interpretation. By accepting the Moon Treaty as valid, some states expressly recognized the permissiveness of resource extraction, and by rejecting it for stifling commercial development, other states also recognized the permissiveness of resource extraction. Finally, ponder the legality of destroying a dangerous asteroid headed for earth.

> "If now any state or group of states had the capability to deflect such an asteroid from its natural orbit, and guide it, for instance, towards the sun, this would of course mean intentional destruction of the said body, and nobody could or would question the legality, and the absolute necessity of such an action. But destruction of an object, a *res* in Latin legal language, is the ultimate appropriation. Surely, this could not be in earnest an act contrary to international Space Law, as it exists. So, is such a small body, for instance, a "Tunguska Meteorite," a Celestial Body in a legal sense, and would anybody be opposed to such an action on such a legal basis?"[70]

As suggested, destroying something is indeed the "ultimate appropriation." However, the point that no one would realistically object to such an action is a powerful one. How does this scenario aid in the understanding of the *CJS*? It does so by demanding a consistent and

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[68] *Id*.
[69] Moon Treaty, *supra* note 14, at art. XI.

[70] Ernst Fasan, *Asteroids and Celestial Bodies–Some Legal Differences*, 26 J. Space .L. 33, 36 (1998) (discussing the difficulties and trends in defining celestial bodies).

workable interpretation of the *CJS*'s terms. While no one might object, destroying this hypothetical asteroid was indeed appropriation, and hence illegal, unless a framework is interpreted that would communicate otherwise. The definition that a celestial body is something that cannot be artificially moved frames the situation perfectly. This definition fits exactly within the *CJS* under the laws of interpretation, and it has the added effect of allowing the retrieval of resources. Resources, when removed, gain their own unique identity when they cease to be part of the parent celestial body. These resources, being movable, are thus not celestial bodies and are ripe for commercial harvesting. It would, indeed, be an "absurd result" under the Vienna Convention to claim that, legally, such a dangerous object could not be destroyed.[71] The destruction of a celestial body fulfills the criteria laid out previously to remove its status as a celestial body, so even the eventual and complete disassembly of an asteroid would be permissible.[72]

While scholarly commentary may seem confused at times, the *CJS* is clear that resources may be retrieved from space and celestial bodies.[73] Patterns of practice and behavior are already well-established to this effect, and the practical reality is that both nations and private individuals are well on their way to doing so on a commercial scale.

Practical Reality

From the earliest days of space faring nations, there have been three ubiquitous resources which have been used by presumption. These

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[71] *See* Vienna Convention, *supra* note 17.

[72] It might be tempting to ask, in light of this sentence, whether or not Dr. Fasan's definition has any meaning at all. Indeed, some may ask what can truly be said to be a celestial body if complete destruction could remove an objects status as a celestial body. This fear is unfounded at best. As already noted, it is easier to move an object than it is to destroy it. Secondly, should technology progress to moving and destroying planet sized objects, the *CJS* would be utterly ill-suited to handle that environment. While it might be academically pleasing to have a definition that serves every conceivable concern and situation, such is not, at the present, feasible.

[73] *See* CHENG, *supra* note 7, at 401. De Man, *supra* note 7, at 17; Dula, *supra* note 7, at 10-12 (discussing currently permissible exploitations and the differences between "use" and "exploitation" under the Moon Treaty).

three resources are solar energy, the gravity well of the Earth [and other celestial bodies], and the vacuum of space. The key aspects are:

- they were there,
- the resources were available for use at some expense and effort, and
- they were subsequently used without challenge.

Commercial entities have used these same three resources without government intervention while substantial profits have been gained. To exploit solar energy, it was necessary to produce space-qualified solar cells, then panels and then arrays. The gravity well of each celestial objects allows satellites to be placed in predictable and repetitive orbits so commerce can be afforded on a reliable basis. Finally, the vacuum of space allows objects once placed in a stable orbit to remain there with little added fuel for many years.

From an engineering perspective, these resources have been used continuously since the first commercial telecommunications satellites [Telstar became operational in 1962]. From an engineering perspective, it seems simple enough to have the international community agree that solar energy, at a minimum, is a space resource that has been used for the benefit of all mankind and for commercial profits for the past 50 years. Indeed, it stands to reason that these telecommunications satellites have demonstrated that the benefit of all mankind occurs by the availability of the product or service and not in the profit stream. This is all accepted practice. It has unquestionably been shown that designated space resources [solar energy, vacuum and gravitational wells] can be used at will and for profit-based businesses as customary international practices. This example has shown that space resources can be identified, extracted, and exploited for profit.

Exercising Jurisdiction in Space and on Celestial Bodies

From an international perspective, several types of jurisdictions exist. First, "a state may employ judicial or non-judicial measures to induce or compel compliance or punish noncompliance with its laws or regulations, provided it has jurisdiction to prescribe…"[74] The power to

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prescribe can be considered as follows. A state has jurisdiction to prescribe law with respect to

> (1) (a) conduct that, wholly or in substantial part, takes place within its territory; (b) the status of persons, or interests in things, present within its territory; (c) conduct outside its territory that has or is intended to have substantial effect within its territory;
>
> (2) the activities, interests, status, or relations of its nationals outside as well as within its territory; and
>
> (3) certain conduct outside its territory by persons not its nationals that is directed against the security of the state or against a limited class of other state interests.[75]

In effect, a state may prescribe jurisdiction over (1) any action within its territory, (2) its nationals outside its territory, and (3) any action that is aimed at harming the state.[76] However, because the non-appropriation principle prevents the exercise of territorial jurisdiction, states are left with an incomplete set of tools to govern and manage their affairs in space.

Fortunately, the OST grants a form of jurisdiction that Cheng has termed "quasi-territorial" jurisdiction.[77] Article VIII of the OST states that:

> "[a] State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body. Ownership of objects launched into outer space, including objects landed or constructed on a celestial body, and of their component parts, is not affected by their presence in

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[74] Restatement (Third) of Foreign Relations Law § 431 (1987).

[75] *Id*., at § 402.

[76] There are additional principles of jurisdiction such as "Universal" and "Victim Theory" which cover breaches against the law of nations and offenses against a state's nationals outside of its territory, but these principles are not relevant to the current discussion.

[77] CHENG, *supra* note 7, at 70-87.

> outer space or on a celestial body or by their return to the Earth."[78]

This draws from the United Nations Convention on the Law of the Sea which states that "[s]hips shall sail under the flag of one State only and, save in exceptional cases expressly provided for in international treaties or in this Convention, shall be subject to its exclusive jurisdiction on the high seas."[79]

By granting quasi-territorial jurisdiction, the OST created the means by which extraterrestrial activities may be properly governed. Cheng specifically describes quasi-territorial jurisdiction by saying that

> "[i]n between territorial jurisdiction and personal jurisdiction stands *quasi-territorial jurisdiction*. This is the sum total of the powers of a State in respect of ships, aircraft and spacecraft (to the extent to which they are also granted legal personality) having its nationality or registration. Its powers over pirate vessels *jure gentium* come also under this heading. Quasi-territorial jurisdiction differs from personal jurisdiction in that it extends not only to the craft in question but also to all persons and things on board, including the activities of such persons, whether on board the craft or elsewhere."[80]

Quasi-territorial jurisdiction gives states the ability to prescribe rules of conduct and properly govern extraterrestrial populations. This concept is heavily reinforced by a 1996 resolution of the UN General Assembly which states that "States are free to determine by their national legislation all aspects of their participation in international cooperation in the exploration and use of outer space."[81] States have always had the

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[78] OST, *supra* note **Error! Bookmark not defined.**, at art. VIII.

[79] *See* United Nations Convention on the Law of the Sea, Dec. 10, 1982, art 92(1), 1833 U.N.T.S. 3, 58.

[80] Cheng, *supra* note 7, at 73.

[81] G.A. Res. 122, U.N. GAOR, 51st Sess., Supp. No. 20, U.N. Doc. A/51/590 (1996).

power to authorize private business to use outer space for commercial purposes.[82] Examples of such authorized commercial use include communications and remote sensing satellites.

Despite its usefulness, quasi-territorial jurisdiction does lack a few of the "sticks" that belong in the "bundle of rights" that comprise territorial jurisdiction. Cheng notes that the rules of international law which govern the positive aspects of territorial jurisdiction will not exist in space because "[r]ules such as those governing the expropriation of private property belonging to foreigners, for instance, would have no application on the moon, even when there is a fair-size population there, until territorial sovereignty has been established and recognized."[83]

The Common Heritage of Mankind and Similar Doctrines

Of all the concepts within the *CJS*, it seems that none is more contentious yet simultaneously lauded than the Common Heritage of Mankind doctrine. Dreaded by developed nations for its redistributive implication, and hailed by developing nations for the same, the CHM doctrine is a greatly debated concept. First admitted for consideration into the OST by the Argentinian representative to COPUOS, the CHM doctrine was not substantively adopted into the *CJS* until its inclusion in the Moon Treaty. Given the Moon Treaty's failure, the CHM doctrine appears non-operative in outer space. However, it might be argued that Article I of the OST's statement that "outer space, including the moon and other celestial bodies […] shall be the province of all mankind" creates a substantially similar or identical regime. Is this the case? Or is

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"States are free to determine all aspects of their participation in international cooperation in the exploration and use of outer space on an equitable and mutually acceptable basis. Contractual terms in such cooperative ventures should be fair and reasonable and they should be in full compliance with the legitimate rights and interests of the parties concerned, as, for example, with intellectual property rights.")

[82] See Kunihiko Tatsuzawa, *The Regulation of Commercial Space Activities by the Non-Governmental Entities in Space Law*, Space Future, *available at* http://www.spacefuture.com/archive/the_regulation_of_commercial_space_activities_by_the_non_governmental_entities_in_space_law.shtml. ("The principle of freedom of outer space includes the right of free access, the right of free exploration, and the right of free use. This freedom is granted only to the States.")
[83] Cheng, *supra* note 7, at 79.

the CHM doctrine defunct, and if so, what does it mean for outer space to be the "province of all mankind"?

What matters most is understanding the substantive and binding sources that might push the CHM doctrine into CIL or the *CJS*. It is unlikely that the nebulous and undefined nature of the CHM doctrine's rule that resources are to be shared has entered into force via CIL. Even if it has, states will still be in a position to interpret it in such a way that will satisfy the rules of interpretation while removing the interpreter's objections.[84] Article I of the OST says that "[t]he exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind."[85] It has been suggested that there is meaningful semantic difference between the CHM and the "province of all mankind," in that the latter phrase is more related to a "concept of a freedom of usage in that a state has the right to participate in the development of outer space. If that state does not somehow contribute to such a program, however, it is not automatically due a portion of the proceeds resulting from that program."[86] Citing *CJS* scholar Stephen Gorove, one commentator stated that:

> "The [OST] gives little guidance as to the manner and extent to which celestial resources are to be distributed to "all" states even though the language of the [OST] "presupposes the ideological if not also the political unity of mankind, a condition which is likely to remain an all too distant goal for some time to come."
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> "Although a strict interpretation of the phrase "all" countries would include all nations, regardless of whether they are recognized as such by the international community,

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[84] Consider the western view that capitalism and commerce is a beneficial activity. It would be a likely interpretation that resource sharing is simply a very broad commerce channel.

[85] OST, *supra* note **Error! Bookmark not defined.**, at art. I.

[86] Weaver, *supra* note 7, at 225.

> Gorove suggests that "the reference to 'all' countries should be viewed as a general statement of policy rather than a specifically enforceable obligation." Moreover, Gorove argues that "the phrase referring to the 'province of all mankind' is presently more of an expression of hope than one of actual content [because] the provision as it stands seems to be a compromise between the interests of the underdeveloped nations and those of the space powers. In any event, the phrase "for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development" seems to have been in line with the aspiration of underdeveloped nations because of its specificity, while reference to the "province of mankind" appears to have suited the space powers because of its vagueness."[87]

Much like the statement that astronauts are the "envoys of mankind," the statement that outer space is the "province of all mankind" has become, if it even was something else to begin with, a provision without true meaning and instead a mere expression of sentiment. Additionally, recall that patterns of practice and behavior are one element of CIL. Currently, few nations, if any, are in a true position to meaningfully appropriate a celestial body. While nations have indeed explored celestial bodies, albeit in the most cursory of ways, they have never been in a position to truly harvest, much less redistribute, the resources of outer space on any meaningful scale. How then can it be argued that practices are established that might shift the CHM doctrine into the *CJS*?[88]

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[87] *Id.*, at 225-26 (citation omitted).

[88] The author notes that this question seems to challenge previous statements made in this work. For example, it was noted that the non-appropriation principle in Article II of the OST has passed into CIL, and this thought is not meant to challenge the notion so much as beg a reexamination as to the strength with which that principle entered into CIL. It seems quite interesting to ponder how a general pattern of practice can develop around a behavior that cannot actually occur due to technological limitations.

While the CHM doctrine certainly exists, it does not live within the *CJS*. As explained, the OST did not incorporate it, and the rejection of the Moon Treaty was an express message that such a concept would not be accepted within the *CJS*.

7.2.5 Resource Ownership Summary

While concerns remain, and scholars say otherwise, the *CJS* is clear that the mineral bounty of space may be freely harvested for the benefit of private parties. Nations are not only free, but required, to resolve definitional ambiguities within the *CJS*. These subsequent practices will reinforce the current law and ensure that the fruits of the universe are available to improve the society of mankind. Some thinkers would have the inventive spirit of man chained by the *CJS*. What was once meant to keep space "free for use" by all, would instead make it free for use by none. Only when the raw creativity of man is respected by the *CJS* will a spatial renaissance take place. That gift has been given, and man must now move forward to claim his bounty among the stars. Like Prometheus with his gift of fire, the gift of freedom and individuality in space will unleash the raw creativity of man, and that is surely "for the benefit and in the interests" of all mankind.

7.3 Specific SMR System Policy Considerations

As this is an embryonic enterprise, several considerations must be evaluated during the development phase. These policy guidelines will be refined as more knowledge on approaches, objectives and engineering/mining techniques are established. Some items of future study are:

- Environmental liability
- Mining Site Maintenance
- Asteroid mining approaches
- Movement of Asteroids to Earth Moon system

One such policy recommendation could be based upon the following statements.

SMR Approach 2: Deliver Product to Lunar orbit – An orbit around the Moon was suggested in the Keck Institute study of asteroid retrieval primarily because any asteroid that drifted out of control would eventually be drawn to impact on the lunar surface. This safety feature comes into play only after an object is delivered; during transit, the risk from that object remains. Therefore, safety should be achieved by never transporting an object large enough to survive Earth entry, regardless of the in-space location chosen for processing.

7.4 Legal and Policy Summary

Nations and individuals seeking to capture the mineral wealth of space face not only technical hurdles but legal ones as well. Space is currently governed by the CJS, a loose body of national and international law. Many nations have enacted laws to oversee domestic space activities; but, the nature of space and such activities demands the attention of the international community as well. Issues such as satellite administration, scientific research, space-based weaponry, and, most importantly, resource utilization all concern third parties. Domestic laws are generally insufficient to allay international concerns in these areas. Thus, international space law has slowly grown to encompass these areas and govern where needed. However, the full reach of international space law is somewhat contested, and debate rages on as to the true meaning and strength of these laws.

International law is generally considered superior to most domestic laws; and, it comes in two main varieties: international agreement, or treaties, and CIL. Treaties are agreements between two or more parties, and they are binding only amongst the agreeing parties. The second main variety of international law is CIL. CIL is any international custom or habit that is 1) part of a general pattern of practice and behavior amongst the international community at large, and 2) part of a general pattern of legal expectation. Both prongs must be simultaneously present for a legal custom to become customary international law, which is considered binding upon all actors on the international stage.

In the CJS, there is disagreement over both the exact meaning of terms used in treaties and over the nature and extent of the customary law of space. At issue are the meanings behind certain terms such as “celestial body” and “spacecraft,” whether or not certain habits and expectations have passed into customary law, and the nature of property rights concerning space borne resources. While debate continues on the topic, one fact has become abundantly clear: nations and individuals are planning to harvest the mineral resources of space, and they will do so sooner rather than later.

This section of the study aims to both understand and develop the legal atmosphere of space mineral resources. For example, some scholars and nations posit that space resources belong to all and may be retrieved and utilized only with the consent of all. Many others suggest that resources may be freely extracted for private use without violation of international law. Which view, if any, is correct? These are contentious questions, but answers are beginning to emerge. This study examines both historical precedent and modern developments in space activities. One aspect of international law is that it is fluid in light of subsequent and dynamic practices. Even if previous activities are, or were, legally questionable, they are, or will become, increasingly legitimate as more actors engage in such behaviors.

The inexorable march of human progress is punctuated by the visionary and the hardheaded alike; and, the efforts of the individuals have not gone unnoticed in the essence of international space law. Nations are beginning to flex their legislative muscle by declaring the permissible bounds of jurisdiction and property in space; and, they are increasingly favoring the view that all space borne resources are free for the taking. From the Isle of Man’s pro private space policies to the United States’ nascent ASTEROIDS act of 2014 that strongly favors the private utilization of space mineral resources, international actors are swiftly moving to cement the shape of the Corpus Juris Spatialis as a workable body of law to fit modern society.

Chapter Eight, Findings, Conclusions, & Recommendations

8.0 Significant Results:

This study was conducted under the assumption that the international space community can make a difference. We, as an industry and as a portion of humanity, can change the current arrow of history so that it points in optimistic directions allowing the human condition to improve and expand. The change that is mandated to accomplish this is to:

Leverage the phenomenal resources available in our solar system.

This Academy study on space mineral resources (SMR) developed preliminary findings and gathered recommendations that should enable commercial enterprises to move forward, and for governments to support them. This effort was a global consolidation of ideas and expert inputs that resulted in the significant conclusion that profits should be achievable while moving into deep space.

Principle Finding: Space exploration missions have been the prerogative of nation states with politics and science as major drivers. Concurrently, industries have grown around the world supporting these missions as well as missions in three arenas: Civil, Defense and Commercial space. Today with the availability of exponential technologies and the reduction of launch costs, private industries are considering economic revenues from space exploration as a major driver for future developments. Use of space mineral resources would be the main source of economic revenues for these corporate risk takers. Industry is aiming to explore and quantify available resources on asteroids and later to initiate the actual use, or harvesting, of mineral resources. Their plans include “prospectors” first and then actual mining of in-situ resources. Technologies were available to explore asteroids by space agencies as early as 1991, well after men landed on the Moon in 1969. However, SMR ventures cannot wait for government programs to lower the risks, both technological and programmatic. Commercial ventures must determine the optimum path for commercial success and aggressively lead the way beyond LEO. During the first half of the 21st century, space leadership will come from commercial enterprises and not be dependent upon government space programs. One concept that would leverage this series of initiatives is to convince government agencies that commercial enterprises will be there first and able to support their explorations by selling products to them at designated locations. As a parallel, to convince investors that use of space mineral resources is a viable business, clear regulatory regimes should be clarified to insure an acceptable risk for return on investment. However the regulatory regime should be flexible and not limiting to industry and innovation; thus, designed to support and encourage commercial ventures in parallel with government space exploration.

Major Conclusion: This Study Group found that mining space mineral resources enables economic travel between the Earth's surface and near-by locations within our solar system. The process of mining water from asteroids, the Moon or Mars will ensure that key elements are available at spaceports of the future. Water will ensure that human exploration will expand beyond low Earth orbit with the profit motive driving exploitation of resources. With this conclusion understood, the following is supported.

Principle Recommendation: A new study group should be "re-energized" from this significant endeavor with a new emphasis placed upon on-going space mineral resource research. The current study discovered that there were many shortfalls in information and that the industry was lacking in key analyses. As it is important to humanity that SMR activities flourish, further study should be emphasizing a more detailed level of analyses identifying critical steps in the evolution towards profitable enterprises. Indeed, the roadmaps incorporated within this report should be expanded to show the risk reduction demonstrations required to grow the necessary technologies to TRL levels 8 & 9. This next level of research should focus on major topics, such as:

- **Technological risk reduction and engineering designs**
- **Legal regime**
- **Psychological and social issues**
- **Economic approach**
- **Asteroid protection parallel**

8.1 Findings:

The following findings were developed in this initial phase of the SMR study:

Finding 1 – Technological risk reduction and engineering design: The mining of asteroids and lunar regolith is within the current state of the technical art. The identification of target mining locations, development of mining equipment and the ability to match those two activities are achievable within today's launch, orbiting, and maneuvering capabilities.

Recommendation 1-1: A follow-on study group should establish a team specifically to look at the design reference missions and necessary engineering steps to achieve mining of space resources. This working group should be established with commercial and academic experts to recommend the type and size of asteroid that should be the initial destination of a prospecting or asteroid capture/return mission. The requirements for commercial space mining firms may be different than the interests of academic scientific experts. This recommendation includes specific tasks:

Task 1-1-1: Initiate multiple year-long comprehensive international trade studies and coordinate with the heads of national space agencies. This should be initiated as soon as possible to establish relative figures of merit and options for different combinations of human and robotic activity that will be required for space mining. An initial action is to coordinate with the ISECG to conduct parallel efforts. [International Space Exploration Coordination Group]

Task 1-1-2: Establish and chair a trade study of interested stakeholders to evaluate ways and means of dealing with the challenge of a long-term radiation environment of space mining. This study has identified radiation exposure as a major technical challenge to large scale space mining operations.

Task 1-1-3: Establish the differences between SMR physics and terrestrial mining and manufacturing. By developing both fields, a series of linked benefits can be created that will cascade across multiple industries. A research program identifying similarities and differences should be undertaken immediately by space agencies. Their goal should be to find novel approaches and to stimulate the development of new technologies that will advance both terrestrial and space mining. Asteroid impact mitigation techniques, new propulsion methods, and alternative energy re-utilization strategies are all areas that will immediately, and directly, benefit from this.

Task 1-1-4: Establish a sub-group that deals with future long duration habitats, both in free-fall and on an asteroid or lunar base. The psychological and social effects "in space" and "on the Earth" of developing space mineral resources on a large scale are unknown. The interested space agencies and the IAA, should work with universities (such as the International Space University in Strasburg, France) to define the parameters of this issue. The study group believes that input from the history of exploration, operations in long term harsh environments, and high stress team work (for example on naval nuclear submarines) could be useful. The benefits to humanity should be quantified and the profit of commercial success should be confirmed.

Task 1-1-5: Evaluate the economic effects in space and on the Earth of developing space mineral resources on a large scale. More analyses on the economic potential of SMR should be carried out by the Academy with assistance from space agencies. Economic modeling is the basis for predicting commercial partner behavior; and, it should be framed in a systems-based context that includes the Earth. For example, it needs to be pointed out that all of the money will be spent on earth. It will create jobs & infrastructure. This will bring vitality to the global aerospace sector, to include:

- Economic trade studies should be created by the new study group regarding the ratio of Earth support jobs per space colonist, using the ISS or MIR experiences as reference points. Detailed costing and architecture will identify profit points; and, it will enable commercial certainty in developing SMR.
- Asteroid retrieval costs are highly dependent upon orbital transfer energy composition and orbital timing (synodic period).

These elements should be studied in detail so that these costs are properly reflected in the standardized SMR economic model.

Task 1-1-6: Work with Space agencies to examine and map the public-private partnership (PPP) crossover trade space within asteroid impact hazards, as it is a compelling international problem. Options that maximize the value of PPP should be identified and promoted, including a trade study of how to create natural incentives and rewards for PPPs using policy & law that minimize public costs and maximize value to private parties.

Finding 2 – Legal Regime: Although space is inherently multi-national and international in its scope, experience indicates that national laws are the only framework that individual actors, both private and governmental, will accept as a means for specifically developing and acting in space. Mining and ownership of space mineral resources is parallel to national laws and, as such, is consistent within current international law. International space law has established that national laws govern national activities in outer space within the current framework. Some national laws need to be amended to facilitate commercial development of space mineral resources. History has repeatedly demonstrated that areas controlled primarily by national, as opposed to international, law prosper most readily (remote sensing, communications, and navigation satellites for example).

Recommendation 2-1: Because an international framework that recognizes national law as a proper tool to develop and control a nation's internal affairs in space already exists. It is recommended that all agencies, governments, and scholars recognize and promote a scheme of domestic law for space activities. A subgroup of the new study, working with Commission 5 and the International Institute of Space Law, should develop a model national code for the regulation of space mineral resources. This study should recommend specific rules to allow transfer of technical information relevant to space mining and to address coordination regimes for space safety for the movement of high mass cargos near the Earth. National space agencies are in the best position to advance and mature the legal environment of space; and, agency heads are the most important individuals in securing the freedom of space for all nations to prosper by its fruits.

Recommendation 2-2: A new study should continue to work with as many national space agencies as possible to build consensus and strengthen international understanding and development of specific processes regarding the legal exploitation of SMR. An inter-agency protocol would be a useful tool to coordinate and develop this consensus and understanding.

Task 2-2-1: Work within the study to stimulate global industrial cooperation for SMR while supporting the IAA follow-up activities to the Hague SMR Governance Working Group. [Hague, 2014]

Finding 3 – Low Cost Access to Space Will Enhance SMR: Although space is inherently multi-national and international in its scope, the financial aspects of any activity focuses upon the initial lift to orbit costs. At the present time, access to space is exorbitant and can only be justified as necessary, as there are no alternatives. The finding is that:

> Low cost access to space will ENABLE space mineral resource activities ensuring that the commercial imperative is supported. Reducing cost of delivery to an EML-1 Lagrangian spaceport by two orders of magnitude will ensure that commercial entrepreneurs will spring up and pursue the vast opportunities then available.

Recommendation 3-1: Continue the effort to create and support commercial launch activities. This study applauds activates such as SpaceX, Orbital Sciences and Boeing in their commercial deliveries to the International Space Station. This should be expanded to delivery of routine products anywhere in the Earth-Moon ecosphere.

Recommendation 3-2: Continue to investigate and develop revolutionary approaches to lower costs to orbit. There are currently multiple efforts that should be encouraged such as reusable rockets, space elevators [both for the Earth and the Moon], larger ion-engines, and the VASIMR approach.

Finding 4 –Timely Study Completion: The conclusion of this Academy study during the spring of 2015 is timely. The results of the 30 month activity have stimulated interest across the spectrum of space professionals in parallel with three ground breaking workshops. These occurred before completion of this document with another session added to the yearly IAF Congress – "Space Mineral Resources, Asteroid Mining and Lunar/Mars In-situ," 12-16 October 2015 in Jerusalem.

- "The Economics of NEOs:" This workshop at NASA Ames Research center was conducted on 6-7 September 2014 with the aim: "… to serve as a catalyst for discussions and to foster collaborations between industry, academia and government." The summary of the workshop was released to the IAA and is presented in Appendix H.
- "Space Mineral Resources Governance:" This meeting was held in The Hague on December 1, 2014. The key result from this activity was the formation of a "Hague Space Policy Working Group."
- "Towards the Use of Space Resources:" This follow-on meeting of the Ames workshop was conducted on 20-21 March 2015, in Luxembourg with the principal focus of understanding the relationship and needs of the commercial ventures and parallel government activities. The workshop was sponsored by the Minister of Economics of the Luxembourg government. Much discussion occurred around risk identification and investment vs. technological readiness level knowledge.

The key feature of Finding #4 is that commercial space ventures are currently aggressively investing in risk reduction and reaching out to form commercial and governmental partnerships. These types of actions, in the past, have led to development of major new industries. This will probably be no different!

8.2 Basic SMR Roadmap

During the study, multiple commercial SMR corporations submitted their roadmaps towards profitable mining operations in space. The basic approach is as follows:

Phase One: **Initiate the business on Earth**
2014-2020
Phase Two: **Execute a prototype flight to potential asteroids as well as testing hardware in LEO**
2015-2022
Phase Three: **Initiate mining operations with return of product**
2018-2029

Chapter Nine, Concept for the Future

After studying the aspects of space mineral resources while comparing them with the needs of our global growing population, a concept for the future has surfaced. The leveraging of space resources should make access to space less expensive and allow phenomenal growth of commercial ventures. Technological inventions will lead to Earth spinoffs and enhance the human condition. Successful commercial ventures will enable people to grow and expand their horizons, to include space activities. Commercial ventures must step out smartly and develop an optimum path for business success and lead the way towards an opening of our solar system. They should not wait for government programs to lower the risks, either technological or programmatic. During the first half of the 21st century, success will grow from commercial space leadership through aggressive ventures benefiting investors, the people on Earth, and the opening of enterprises in space.

The idea that has motivated this commercial space concept is the simple idea of supplying water [which is also fuel, air, oxygen, and power] to explorers and commercial ventures within the Earth-Moon economic sphere. Prospecting for and developing water-rich sites, processing water, storing it, moving it, and then selling it will enable companies to make a profit and supply necessary resources to all travelers.

Establishing spaceports and selling water that was mined from the Moon or asteroids will enable growth into our solar system. This growth will be remarkable because the essential elements come from lunar or asteroid water sources at a much cheaper price than lifting it from the surface of the Earth. When one realizes that fuel is over 80% of the mass at an Earth surface launch site when trying to reach lunar orbit, one recognizes that the price for a payload in orbit is exorbitant. The economics show that the price to develop water sources on the Moon or on asteroids is two orders of magnitude below the delivery price from Earth. A commercial venture of selling Lunar or asteroid sourced water should be successful. During the history of mankind's exploration, many early commercial ventures succeeded by finding local resources that they could sell to explorers and settlers. In the Earth-

Moon economic sphere, that resource is water. The concept that has developed is simple:

Water is the Currency of Space!

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Appendices

Appendix A: IAA Study Participants

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Contributers

Study research staff: Mr. Brad Blair, Ms. Anat Friedman, Ms. Shiro Khan, Mr. Jason Juren

Organizations contributing:

The Heinlein Prize Trust
U.S. National Space Society
International Space Development Conference
Texas A&M University – Aerospace Engineering Department
European Space Conference – Turino
Newspace Conference
International Space University
International Space Elevator Consortium
Chinese Society of Astronautics
Canadian Space Society
Australian Space Society

Commercial Firms contributing:

Planetary Resources
Moon Express
Excalibur Exploration Limited
Deep Space Industries
Ad Astra Rocket Company

Appendix B: Glossary of Terms and Acronyms

ACES	Advanced common evolved stage	LMO	low Mars orbit
ADCS	attitude determination and command system	LOX	liquid oxygen and hydrogen
AIAA	American Institute of Aeronautics and Astronautics	LOX/H2	liquide oxygen and hydrogen
APA	Advanced pricing agreements	MCC	mission control complex
ARM	asteroid redirect mission	MEO	Mid Earth Orbit
ASAP	as soon as possible	MER	Mars Exploration Rover
ATP	US Commerce Dept. Advanced Technology Program	MEV	Mega electron volts – [million]
CCSDS	Consultative Committee for Space Data Systems	MilStd	US Military Standards
CHM	Common heritage of mankind	MIR	USSR space station
CIL	Customary international law	MSL	Mars Science Laboratory
CJS	Corpus Juris Spatialis	MT	metric tons
CME	Coronal mass ejections	NASA	National Aerospace and Space Administration
CO2	Carbon Di-Oxide	NEA	near Earth asteroid
COTS	commercial off the shelf	NEO	Near Earth orbit
CSA	Canadian Space Agency	NHATS	NEAs Human Space Accessible Targets Study
DII	Directors Innovation Initiative [NRO]	NIAC	NASA Innovative Advanced Concepts
DRM	Design reference mission	NPV	Net present value
ECLSS	Environmental Control and Life Support System	NRO	National Reconnaissance Office
ECSS	European Coordination for Space Standardization	OPEC	Organization of the Petroleum Exporting Countries
EERE	US Dept Energy's Energy Efficiency Renewable Energy	ORU	Orbital replacement unit
EML-1, 2	Earth Moon Lagrangian Location # 1, or 2	OST	Outer Space Treaty
ESA	European Space Agency	PGE	platinum group elements
ETO	Earth to orbit	PPP	Public Private Partnerships
EVA	extra vehicular activity	PV	present value
FAA	US Feberal Aviation Administration	R&D	research and development
FV	future value	RAP	Robotic asteroid prospector
GCR	Galactic Cosmic Radiation	REE	Rare Earth elements
GDP	gross domestic product	ROI	Return on Investment
GEO	geosynchronous Earth orbit	ROM	Rough order of magnitude
GES13	Global exploration strategy 2013	SBIR	Small business innovative research
GEV	giga electron volts – [billion]	SDO	Standards Developing Organizations
GLXP	Google Lunar X-Prize	SE-AA	Space elevator apex anchor node
GOST	Gosstandart Standards [Russian]	SE-GEO	Space elevator geo node
GPS	Global Positioning System	SEC	Securities and exchange commission
GTO	geosynchronous transfer orbit	SEI	Space exploration initiative
IAA	International Academy of Astronautics	SEP	Solar Energetic Particle events
IAS	Internationa accounting standard	SETI	Search for extraterrestrial intelligence
IAS	international accounting standard	SIF	Space infrastructure forecast
ISECG	International Space Exploration Coordination Group	SMR	Space Mineral Resources
ISO	International Standards Organizsation	SSP	Space Systems Power or Space Solar Power
ISP	Specific Impulse – measure of rocket efficiency	STEM	Science, technology, engineering and mathematics
ISRU	in-situ resource utilization	STP	Solar thermal propulsion
ISS	International Space Station	STS	space transportation system – Shuttle
ITU	International Telecommunicaiton Union	TRL	technology readiness level [levels 1 to 9]
JAXA	Japanese Space Agency	UNCLOS	United Nations Convention on the Law of the SEA
JORC	Australasian joint ore reserves committee	UNCOPUOS	UN Committee on Peaceful Uses of Outer Space
JSC	Johnson Space Center	USD $	United States dollar
KPI	Key performance indicators	VASIMR	variable specific impulse magnetoplasma rocket
KRI	Key risk indicators	WACC	weighted average cost of capital
KSC	Kennedy Space Center	WARC	World administrative radio conference
LEO	Low Earth Orbit	WBS	work breakdown structure
LIDAR	Light Detection and Ranging	WGER	Working group on extraterrestrial resources
LLO	low lunar orbit		

Appendix C: IAA Study Terms of Reference

Proposal for Forming an IAA Study Group SG 3.17

Title of Study: Space Mineral Resources – Challenges and Opportunities
Proposer(s): Mr. Arthur M. Dula
Primary IAA Commission Preference: 3, Space Technology & Systems Development
Secondary IAA Commission Interests: 1, Space Physical Sciences; 3 Law, Economics & Policy
Members of Study Team
Chair(s): Mr. Arthur M. Dula, + TBD
Secretary: Ms. Anat Friedman
Other Members:
Mr. Roger Lenard
Mr. Hans E. W. Hoffmann Mr. Bohdan I. Bejmuk
Dr. George C. Nield Professor Li Furong
Mr. Hiroshi Yoshida Professor Oleg Alfanov Others TBD

Short Description of Scope of Study Overall Goal:
To provide a logical, systematic and practical road map to promote and encourage near term evaluation, development and use of space mineral resources (SMR) in space
Broad areas outline of the proposed study:
1. Type, location and extent of SMR; Lunar, Asteroid, Mars, others.
2. Currenttechnicalstateoftheartintheidentification,recoveryanduseof SRM in space and on the Earth that identifies all required technical processes and systems, and that makes recommendations for specific technology developments that should be addressed near term at the system and subsystem level to make possible prospecting, mineral extraction, beneficiation, transport, delivery and use of SMR. Particular attention will be dedicated to study the transportation and retrival options available for SRM .
3. Analysis of the legal, regulatory and policy issues that control, limit, promote and are related to the development and use of SMR in space and on the Earth, including right to use SMR under current international and national laws, with identification of unresolved legal and regulatory issues and recommendations for action to resolved potential roadblocks.
4. Analysis of business and business issues related to development and use of SMR in space and on the Earth with pro forma case studies. Particular attention will be paid in evaluating the economical aspects related to the SRM. A broad spectrum of potential stakeholders, including international mining and resource development firms, banking and capital market will be identified
5. Development of several specific technical, legal and economic "road maps" for SMR development and use in space and on the Earth.

6. Conclusions and recommendations.

N.B.: Although some books and/or scholarly and popular papers have heretofore been published on space mineral resources, to the best of the proposer's knowledge no comprehensive summary of the current literature on this subject is now publicly available. Unlike space solar power, space mineral resources has not been the subject of government or industry funded studies. This proposed IAA study would be the first comprehensive study of the subject and thus should be of significant value to its development for the benefit of humanity.

Intermediate Goals:
Form subcommittees of experts in the areas of technology, economics, law and policy by mid November 2012.
Establish technical means for holding regular electronic meetings of the study group and it's subcommittees by the end of November 2012. Set a regular schedule of meetings, assign responsibilities and agree on a schedule of work by the end of December 2012.
Invite participation of existing stakeholders in Canada and Australia to coordinate cooperation between the study committee and planned conferences in those countries in 2013 to allow the study group to obtain a broad spectrum of opinions from experienced mineral extraction, processing and marketing firms.
Work with IAA Commission 3 to present a draft report as part of the IAA activities to be held in conjunction with the 64th IAC in October 2012 in Beijing, PRC.

Methodology: Hold regular electronic meetings of the study group. Agree to specific assignments and deadlines once the work outline has been drafted. This study is a volunteer effort, but it will be managed professionally and there will be a clear understandings and acceptance of rolls and responsibilities.

Time Line: October 2012 to March 2015

Final Product (Report, Publication, etc.)
Cosmic Study report published by IAA or other Sponsor
Publication in an aerospace journal (TBD)
Workshop in the period of the IAC in 2013 in Beijing in October 2013 or earlier
Press conference with the main outcome of the Cosmic Study

Target Community:
Commercial space scientific, technical and business community;
Mineral extraction, processing and marketing firms worldwide;
Space policy makers and officials responsibility for assuring adequate future supply of critical minerals;
Capital and banking groups that finance aerospace, mineral extraction and processing; Aerospace engineers and space scientists.

Potential Sponsors:
The Heinlein Prize Trust Excalibur Exploration Limited

Date: November 5 , 2012
(No Signature required if document authenticated). ***Follow-up Section for IAA use only***
by fax: 33 1 47 23 82 16 or
by email: sgeneral@iaamail.org

Initial Phase
Application received: Nov 2012
Commission Approved: Mar 2013
SAC Approved: March 2013
Members Formally Appointed by IAA: March 2014

Final Phase
Peer Review by Commission Completed: March 2015
Recommended by the Commission: March 2015
Final Report Received: March 2015
SAC Approved: April 2015
BOT Accepted: May 2015
Publisher Selected: Yes, Study Published: Spring 2015

Appendix D: Need for Water

To show similar results to support the conclusions of this analyses that water can become a very valuable SMR, the authors show the summary of the results of NASA's RAP study. Indeed, the conclusion is:

Providing water to the EML-1 refueling spaceport
leads to commercial profits.

RAP Asteroid Mining Cost Model – Costing of the RAP architecture utilized parametric cost estimation methods to arrive at development, production and operations cost estimates for the 12-mission architecture.

> *"Factored against these prices and assumed market elasticity (how much the price might change with an increase in supply) the team instead developed a parametric cost model to build, operate, and return the RAP spacecraft and its payload to the Earth-Moon system."* [Zacny, 2013]

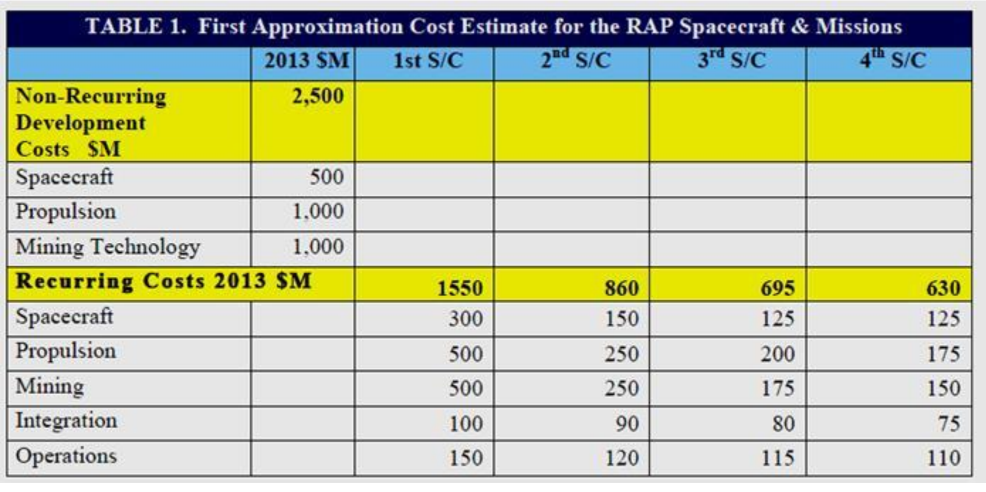


TABLE 1. First Approximation Cost Estimate for the RAP Spacecraft & Missions

	2013 $M	1st S/C	2nd S/C	3rd S/C	4th S/C
Non-Recurring Development Costs $M	**2,500**				
Spacecraft	500				
Propulsion	1,000				
Mining Technology	1,000				
Recurring Costs 2013 $M		**1550**	**860**	**695**	**630**
Spacecraft		300	150	125	125
Propulsion		500	250	200	175
Mining		500	250	175	150
Integration		100	90	80	75
Operations		150	120	115	110

Table 7.19. Estimated recurring costs for RAP architecture [Cohen, 2013b].

The cost estimate [using $ US] for the RAP spacecraft was based upon previous interplanetary spacecraft. It included a development cost of $500M exclusive of mining equipment and the Solar Thermal Propulsion. The production cost of the spacecraft would be $300M based upon its estimated mass. Refurbishment cost of the spacecraft between missions was estimated at 10% of the procurement cost. Learning curve benefits were not assumed. Development cost of the Solar Thermal Propulsion system was placed at $1B. An estimated development cost of $1B for the mining/extraction systems, with an estimate a production cost of $300M for this equipment. Thus, the full development cost for this spacecraft was estimated at $2.5B. Spacecraft unit cost of $900M per unit was estimated. Five years were allocated for the development program. It was assumed that it would take three years to manufacture each spacecraft, and cost $375M to launch a spacecraft. Assembly in LEO was assumed, it would then ferry itself to EML-1. Each launch from EML-1 would cost $50M. The operations cost for the first spacecraft would be $40M per year. Each additional spacecraft added $2.5M to the annual operations budget.

Unit propellant costs were estimated for delivery of water by the RAP spacecraft to EML-1 as shown in Figure 7.14 below. Presumably the expansion of production from an early total of 1,800 tons over 12 missions to later delivery of over 41,000 metric tons of water annually to EML-1 would be achievable at or below the minimum water cost shown below of $5,100 per kg. This, of course, assumes steady-state long-term operations of the RAP system.

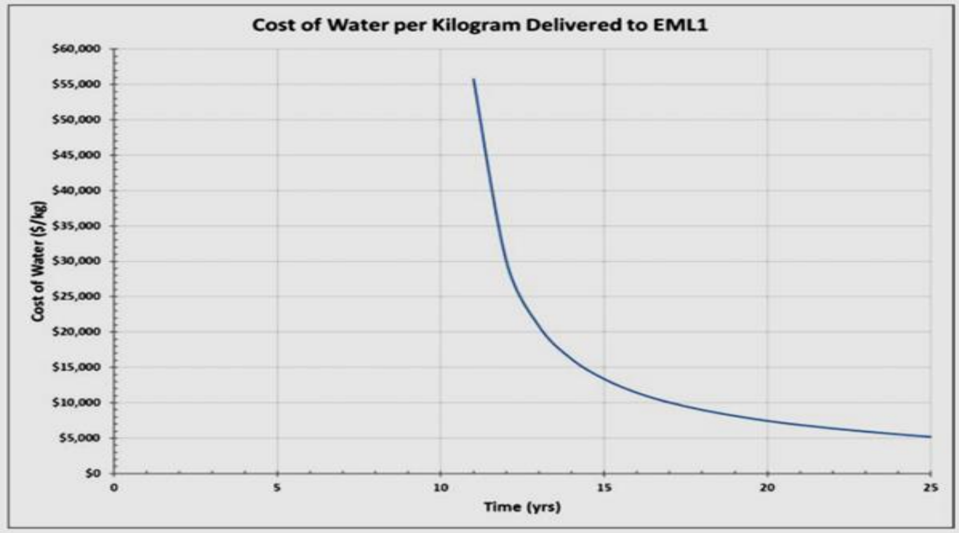


Figure 7.14. Unit cost of water delivery to EML-1 for RAP architecture [Cohen, 2013b].

While vastly oversimplified, this unit cost approach is useful for building a preliminary estimate of future revenues by using the quantitative demand developed in the previous section. However, the approach is still missing one final element - the establishment of a pricing model. Note that this unit cost approach bounds a minimum level of cost. Provided the costing and technical assumptions are accurate, costs could be lower; but, they will not rise above the predicted level. If this system were real, it would actually provide data as well as an economic incentive for competitors to go after a lower cost function. This would stimulate design and development of other asteroid mining architectures while providing a context to evaluate their efficacy.

Appendix E: Need for Nickel

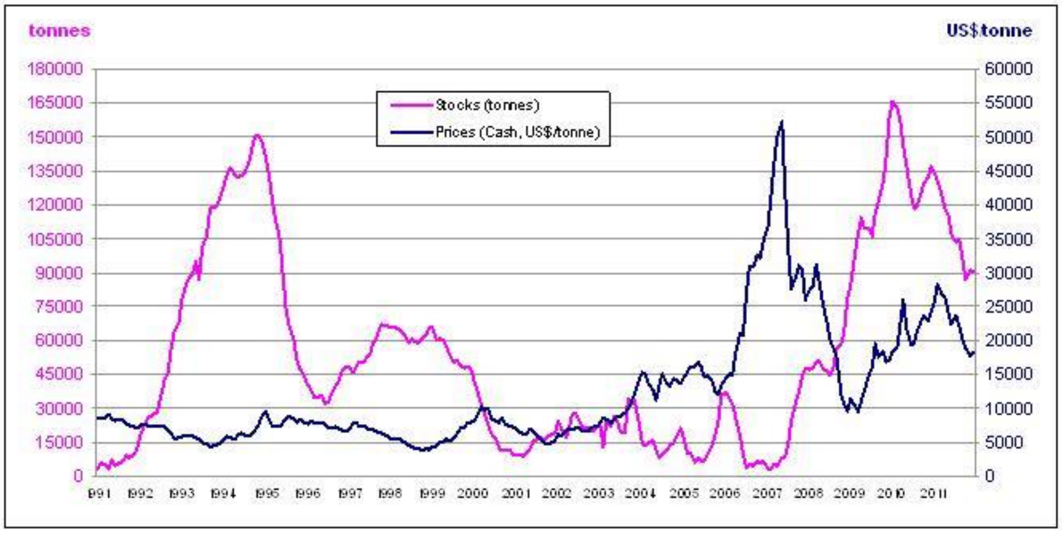
Perceived Goal: Deliver 10% of the world's nickel demand each year from an asteroid. Would this result in a company that is worth $30 billion and makes $3 billion a year? The facts are below:

Nickel demand: Usage of nickel has increased over time and is correlated with economic development. In the past decade world nickel demand increased from 1.104 million tonnes in 2001 to 1.572 million tonnes in 2011, an annual average growth rate of 4.2%. However, the upward trend has had peaks and valleys. 2011 saw the greatest demand for nickel; but, in 2007 demand declined to 1.323 million tonnes as the global economic crisis unfolded and in 2008 demand dropped again to 1.286 million tonnes. A further decline was encountered in 2009 to 1.241 million tonnes. Demand rapidly increased in 2010 to 1.464 million tonnes, and continued improving to a record level of 1.572 million tonnes in 2011. Asia is now by far the largest regional market for nickel representing 65% of total world demand. China alone now accounts for close to 44% of world nickel demand compared with 8% ten years earlier.

First Use: Because nickel is usually recycled, a distinction is often made between the use of newly produced metal and recycled scrap. 'First use' refers to the destination of newly produced nickel. By far the most important use of new nickel is the production of stainless steel. This use accounts for close to two thirds of first use nickel, up from one-third in the past three decades. The market for stainless steel is growing at the rate of about over 5% per annum. Other sectors of first use include other alloyed steels, high nickel alloys, castings, electro-plating, catalysts, chemicals and batteries.

Nickel production: Strong world economic growth, until 2007, supported rising production of primary nickel metal. In 2007, world primary production stood at 1.416 million tonnes. However, the economic crisis led to lower worldwide nickel production in the period 2008 to 2009, and production of primary metal declined to 1.32 million tonnes in the latter year. Production rapidly recovered in 2010 to 1.446 million tonnes and increased further to 1.589 million tonnes in 2011. On an annual average the growth in production between 2001 and 2011 was 3.7%. A new product started to be produced in China in 2005 and that was Nickel Pig Iron (NPI) in different forms and grades. Production increased slowly in the first few years; but, in 2010 production was estimated at over 160,000 tonnes, and in 2011 production could be as high as 250,000 tonnes. Basically all of this product is used domestically in China in the production of stainless steel and has replaced traditional products like nickel metal and stainless steel scrap. In addition to new NPI production in China, several other nickel projects around the world started during this 10 year period. Examples are Barro Alto and Onça Puma in Brazil with a combined capacity of over 100,000 tonnes per annum when in full production. In Madagascar the Ambatovy project is still under construction with a capacity of 60,000 tonnes, Myanmar will have its first nickel project in Tagaung Taung, which should start production in 2012. In New Caledonia, Vale's Goro project has been commissioned, but is still in slow ramp up mode.

Nickel price and stocks: The price of nickel has shown considerable volatility over the last forty years. The chart below shows the historic LME price for nickel in nominal values from 1991 to 2011. In the late 1980s there was a peak in the price of nickel. In the first half of the 1990s the economic collapse of the former "Eastern Bloc" countries resulted in a surge of nickel exports that drove nickel prices lower than the cash costs of production resulting in reduced nickel production in the "West". Until 2003 the nickel cash price remained below US$10,000 per tonne. The price breached $14,000 per tonne in 2005, and then escalated dramatically through 2006, before peaking at an average of $52,179 per tonne in May 2007. Nickel prices then declined until the end of 2008, when the average cash price in December hit a low of $9,678. In early 2009, nickel prices began to once again climb and reached $24,103 by the end of 2010. In 2011 the price continued up and reached the peak in March, with a price of $26,015 and has the basically declined since then and finished off in December at $18,144. A recovery in January 2012 to $19,815 was encountered.



Conclusion: The price of nickel will be sufficient to make a huge profit if delivery of material can be structured with a price less than $ 15,000 per tonne.

Appendix F: Strategic Global Scenarios

Global scenarios spanning from worst-case to best-case are outlined and offered for consideration. Asteroid impact is serious business – it wiped out the Dinosaurs and set back 100 Million Years of biological advances. On the other extreme, SMR could enable our highest visions in science fiction to become reality.

6.2.1 Asteroid Impact – Species Termination

While statistically unlikely, asteroid impact scenarios do include the end of the human race. For the first time in the history of planet Earth, extinction-level events can be mitigated should the collective will of today's dominant species turn its attention toward the danger in sufficient time. If the Dinosaurs had a space program, they might still be running the show.

"In this century a number of events could extinguish humanity. The probability of these events may be very low, but the expected value of preventing them could be high, as it represents the value of all future human lives. We review the challenges to studying human extinction risks and, by way of example, estimate the cost effectiveness of preventing extinction-level asteroid impacts." [Matheny, 2007]

The importance of planetary defense is clearly very high, yet while it is strongly correlated, the purpose of this report is SMR not defense. Therefore, the extensive details regarding the level of danger, mitigation concepts and international policy prescriptions related to defending Earth from the asteroid impact hazard are largely left to readers to discover. However, the defense issue will show up again in the conclusions and recommendations under the topic of public-private partnerships. It also has direct economic implications.

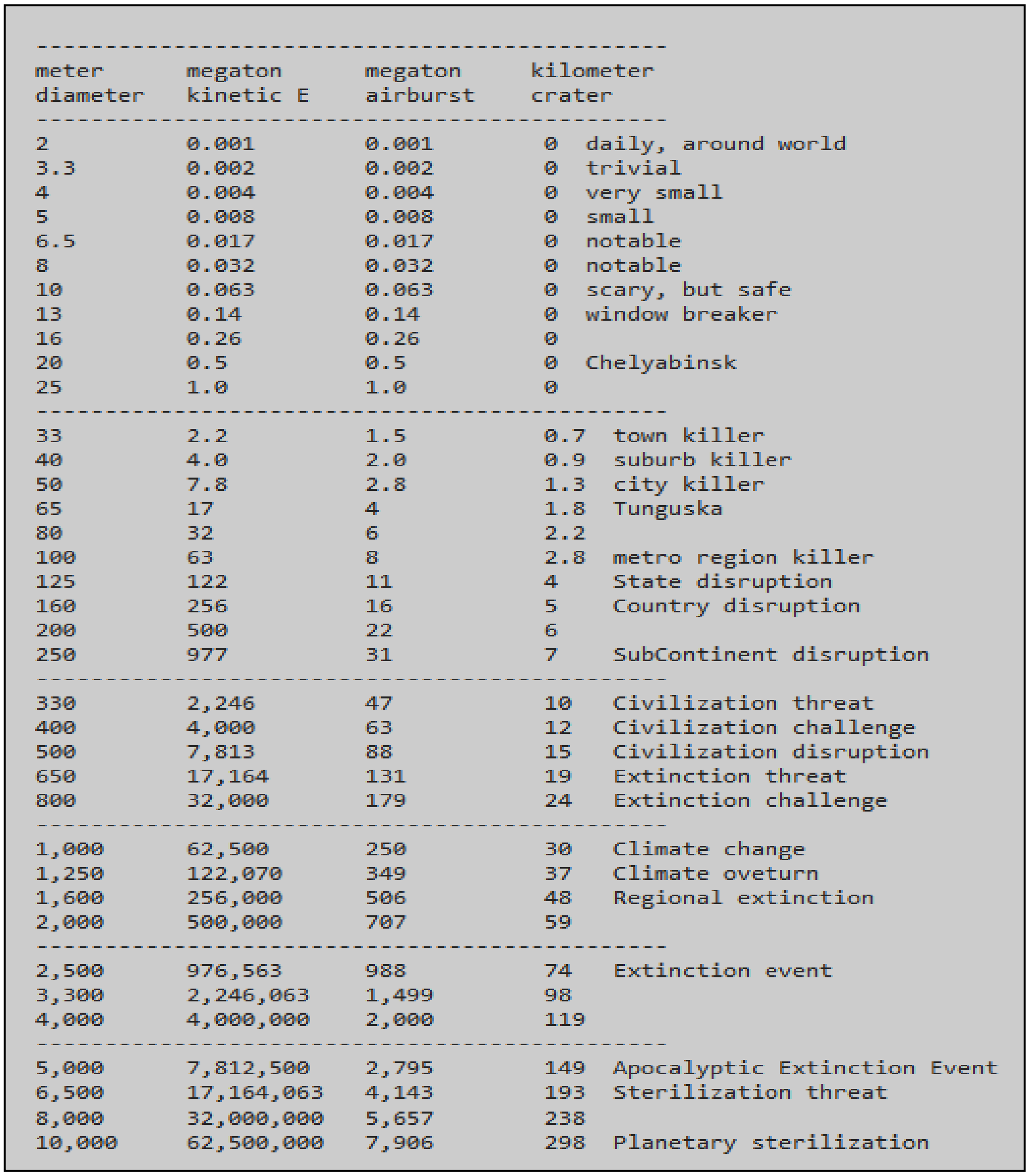
"If we expected humanity to become extinct within a generation, traditional statistical life valuations would warrant a $16 billion to $32 billion annual investment in asteroid defense." [Matheny, 2007]

Quantitative economic methods can and should be used to estimate the value of offsetting defense-related public costs through partnerships with private agents. This process can provide a basis for evaluating the effectiveness of policy changes as well as leveraged public-private investments.

6.2.2 Asteroid Impact – Civilization Ends

A much higher probability event would be a civilization-ending impact. This would be due to a smaller asteroid impact than a planet-buster, one that threatens perhaps one continent and which could spark a global resource reallocation battle that could precipitate collapse. The point is that civilization is a relatively fragile thing, and smaller asteroid impacts could spark larger social reorganizations than just the regions they scar.

"Only about 10 percent of the 13,000 to 20,000 asteroids bigger than 140 meters have been detected. If an asteroid of that size were to strike land, it "could devastate the better part of a continent," Holdren said. Looking on the bright side, Holdren added that such asteroids are thought to hit Earth only every 20,000 years or so. Bolden said less than 1 percent of the space rocks in the 30 to 100 meter range have been found. Such asteroids may not be continent-killers, but they are bigger and more potentially destructive than last month's Chelyabinsk meteor." [Boyle, 2013]



```
----------------------------------------------
meter      megaton      megaton     kilometer
diameter   kinetic E    airburst    crater
----------------------------------------------
2          0.001        0.001        0  daily, around world
3.3        0.002        0.002        0  trivial
4          0.004        0.004        0  very small
5          0.008        0.008        0  small
6.5        0.017        0.017        0  notable
8          0.032        0.032        0  notable
10         0.063        0.063        0  scary, but safe
13         0.14         0.14         0  window breaker
16         0.26         0.26         0
20         0.5          0.5          0  Chelyabinsk
25         1.0          1.0          0
----------------------------------------------
33         2.2          1.5          0.7  town killer
40         4.0          2.0          0.9  suburb killer
50         7.8          2.8          1.3  city killer
65         17           4            1.8  Tunguska
80         32           6            2.2
100        63           8            2.8  metro region killer
125        122          11           4    State disruption
160        256          16           5    Country disruption
200        500          22           6
250        977          31           7    SubContinent disruption
----------------------------------------------
330        2,246        47           10   Civilization threat
400        4,000        63           12   Civilization challenge
500        7,813        88           15   Civilization disruption
650        17,164       131          19   Extinction threat
800        32,000       179          24   Extinction challenge
----------------------------------------------
1,000      62,500       250          30   Climate change
1,250      122,070      349          37   Climate oveturn
1,600      256,000      506          48   Regional extinction
2,000      500,000      707          59
----------------------------------------------
2,500      976,563      988          74   Extinction event
3,300      2,246,063    1,499        98
4,000      4,000,000    2,000        119
----------------------------------------------
5,000      7,812,500    2,795        149  Apocalyptic Extinction Event
6,500      17,164,063   4,143        193  Sterilization threat
8,000      32,000,000   5,657        238
10,000     62,500,000   7,906        298  Planetary sterilization
```

Table 6.1. Asteroid size-danger chart [Wong, 2013]

The difference between an end to modern civilization and broken windows is substantial, yet many uncertainties remain. Economic methods can and should be developed to estimate the value of investment in statistical discovery as well as mitigation technology. This type of basic research will help craft policy and law that will serve the highest good of mankind. The premise is that asteroid hazards could begin to be mitigated with simply the right research focus, and we can do something about the problem starting today.

6.2.3 Global Conflict – Civilization Declines

Humanity could easily take itself out without the help of an asteroid impact. Global aggression is a very real threat. A number of scenarios exist from nuclear exchange to environmental change to resource depletion that could trigger a rapid collapse of social and technological support systems. Dependencies within the global economy may become inadvertent amplifiers of systemic shock or other contagions [Korowicz, 2012]. The end result would the rapid loss of the capability for space access and thus the *option* of robust space settlement.

"The lessons of history would suggest that civilisations move in cycles. You can track that back quite far – the Babylonians, the Sumerians, followed by the Egyptians, the Romans, China. We're obviously in a very upward cycle right now and hopefully that remains the case. But it may not. There could be some series of events that cause that technology level to decline. Given that this is the first time in 4.5bn years where it's been possible for humanity to extend life beyond Earth, it seems like we'd be wise to act while the window was open and not count on the fact it will be open a long time." Elon Musk [interview by Carroll, 2013]

SMR offers a way out of this scenario. The very systems that kept Nations safe in the past now run the risk of killing their host, and must transform in order for humanity to not only survive, but thrive. One of the greatest policy challenges of our time is how to refocus corporate elements supporting the defense of nations from war to more peaceful activities. Capitalism provides a compelling motive for aggressive corporate action: chasing economic profit. This motive, if applied to SMR, could entice highly-effective and well-organized corporations into a more productive form of aggression – enabling the next gold rush.

International technological progress is accelerating, pushing us into new relationships with each other and nature. The potential misuse of these new tools threatens society with imminent collapse. Without a proper creative outlet, the likelihood of one or more collapse scenarios remains high [Korowicz, 2013]. By converting swords into plowshares, humanity can redirect a powerful destructive force into unprecedented capabilities for advancing exploration and settlement. Indeed, a global defense force should target Potentially Hazardous Asteroids (PHAs – a subset of near-Earth objects or NEOs) and Space Debris as its first enemy. Some elements of this exercise have already begun.

"Players consistently remarked that the complexities and overlapping nature of this contingency required advance delineation of responsibilities, formalization of the notification process, and clarification of authorities and chains of command, including authorities for delegation and supported/supporting relationships. Players thought it was important to think through and document this prior to any actual NEO emergency." [Hiss, 2008]

ITAR is a factor that could limit the ability for U.S. leadership in global scenarios. An exemption that frames SMR technology more akin to mining & mineral processing than munitions technology could help mitigate this. Without this policy directive, ITAR could actually create an advantage for non-US government agencies and private companies interested in SMR.

6.2.4 Business as Usual – Nothing Changes

Space exploration is currently dominated by robotic systems, a few humans moving gradually forward and sometimes backward (e.g. Apollo), timid steps and risk-averse decision making. Heritage is a recipe for slow growth of new technology and capability. NASA has learned many hard lessons in how not to conduct a government space program. A side effect of the transparency in which the agency operates is that its learning curve is often all too public. One unfortunate outcome of the management structure inherited from Apollo is weak central command (HQ) with strong centers. Congressionally-supported battles over limited budgets have exacerbated this problem. Add to that the periodic imprinting of new mandates from the executive branch, and it has become a recipe for disaster. The risk of program cancellation dominates the decision tree for any initiative with a lifetime longer than four years. Because the time needed to organize and develop a campaign for human space exploration is typically 8-12 years, a series of failed programs liters NASA's doorstep. It is unfortunate indeed that this was anticipated in 1961.

"Looking into the future, when the space frontier has been explored and is ready for economic development, we might well find the area preempted

by the government, which would then have most of the personnel and facilities available. This would leave the nation almost no choice except to settle for nationalized industry in space." [Cordiner, 1961]

Today China has a rover on the Moon and its own space station. Given current trends, the Chinese could easily become the next dominant power in space. The reason for the rise of the dragon is a matter of dedication, cost effectiveness, unity of purpose and simple follow-through. China is not alone in rising to a new level of space power:

"while Russia plans a new Vostochny Cosmodrome and leads the world in commercial launches, elements in the United States Congress and the space-industrial complex fight to keep NASA mired in a 1960s model that assures the government controls U.S. access to space — and doles out jobs to the districts of Congressional representatives on the space subcommittees." [Smith, 2011]

There have been two countries with the capability to launch humans into orbit for over fifty years. Today the two countries are China and Russia. Cancellation of the Space Launch Initiative in 2003 effectively stopped work on a replacement for the aging Shuttle. While the US space program progressively immolates itself, international competitors gain advantage. Despite its cost to the taxpayer, the highly successful NASA inter-center rivalry system actually enhances careers, creating a negative feedback loop that sharply reduces system efficiency.

Attributes for a successful government space program include:
Smart, empowered people with modern tools
Well organized systems with healthy feedback loops
A unified management structure (no institutionalized infighting)
Management that is empowered to reward success and punish failure
Clear goals
Full support of the political system

International space agency progress in *exploration* is identifying and charting vast new territory, new lands that may be coming into the collective reach of advancing technology for human settlement. But is government-lead space *development* the right approach? To answer that question one must examine reward systems for optimal behavior.

It may be possible to utilize a tried and tested governance system that could naturally maximize the rate of space infrastructure growth and development.

6.2.5 Civilization Boldly Advances into Space

Left to its own devices, commercial enterprise will naturally follow explorers into promising territory. Privately-financed geosynchronous satellites are testament to that process for the space frontier. Indeed, visualizing an expanding three-part sphere of influence composed of exploration, economic development and mature economic operation is useful to describe highly successful prior empires from the Phoenicians, to the Romans, to England and more recently the USA. As shown below, this model can describe our future settlement of space. Prospects will turn into mines, ore turns itself into products, and space manufacturing will feed an expanding space support infrastructure.

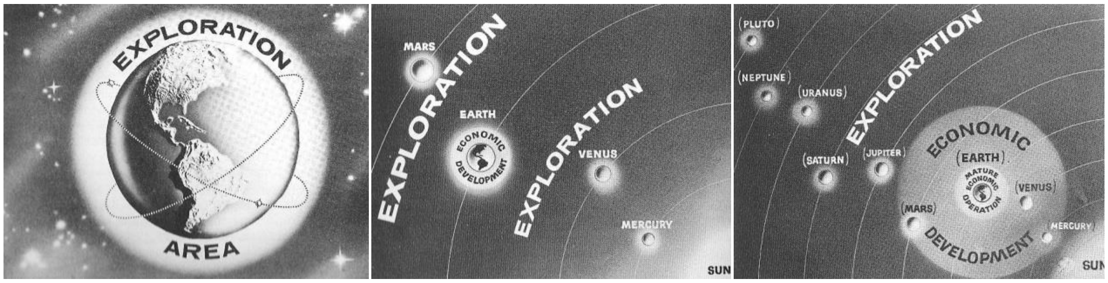


Figure 6.3. Space exploration, development and mature economic operations [Cordiner, 1961].

The expansion of humanity into the next frontier requires the right kind of feedback loop in order to maximize the rate of growth. Crafting a reward system that incentivizes risk taking can be achieved through the fabrication of a healthy system of governance. History reveals that in order to maximize the development rate of a frontier, competitive free enterprise and free markets are more effective than top-down management control. It is great for planning, but often falls short on execution. In the end, the entrepreneurial spirit and availability of venture capital may be the last great hope of the US space program.

“The competitive system, with its profit-and-loss disciplines puts men and companies to the test as no other system does. It rewards the creative and the efficient. It penalizes the unimaginative and the in efficient. It provides an incentive for risk not only on the obvious ideas, but also on the "long

shots." It provides a natural and effective system for the elimination of failure, complacency and delay. At its best, the competitive economy has a vigor, diversity, creativity and efficiency that no controlled economy can match … practically speaking, the system of competitive private enterprise has enabled this country to produce a level of living that is unmatched anywhere, anytime.” [Cordiner, 1961]

The final scenario offered here could be seen as a new golden age for humankind. The prospect of a new gold rush in space is very real. The power of the entrepreneurial spirit in an environment of free enterprise and especially free markets has changed the world. Indeed, it is the keystone of modern Chinese power, and is what made the U.S., European and Japanese economies strong.

The physics of SMR is the most compelling enabler for rapid expansion and geometric growth. However, translating that physics into the language of economics must be done in order to access the capital needed in order to build the supporting infrastructure. Why build that infrastructure? Because today’s surplus of sequestered capital can then be converted into long-term cash flows – making companies and entrepreneurs very wealthy in the process.

Appendix G: International Academy of Astronautics

A Brief Description

Founded: 16 August 1960, Stockholm, Sweden, by Theodore Von Karman. Independent non-governmental organization recognized by the United Nations in 1996.

Aims: Foster the development of astronautics for peaceful purposes;
Recognize individuals who have distinguished themselves in space science or technology;
Provide a program through which members may contribute to international endeavors;
Promote international cooperation in the advancement of aerospace science.

Structure: Regular Meeting (every two years). Board of Trustees (meets twice a year), consisting of: President; four Vice-Presidents and twenty-eight Trustees, seven from each Section: Basic Sciences, Engineering Sciences, Life Sciences and Social Sciences. Current President: Dr Madhavan G. Nair, Past-President: Prof. Edward C. Stone, USA, Vice-Presidents: Mr. Yannick d'Escatha, France; Prof Liu Jiyuan, China ; Dr. Hiroki Matsuo, Japan; Prof. Anatoly Perminov, Russia, Secretary General Dr. Jean-Michel Contant, France.

Activities: Encourage international scientific cooperation through scientific symposia and meetings in the area of: - Space Physical Sciences, - Space Life Sciences, - Space Technology and System Development, - Space Systems Operations and Utilization, - Space Policy Law and Economy, - Space and Society Culture and Education. 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 endeavors in: - The exploration and habitation of the solar system and beyond; - The space debris, - The small satellites, - Declaration of Principles Concerning Activities Following the Detection of Extraterrestrial Intelligence, - EVA Safety and Space Suit Interoperability, - Inexpensive Scientific Satellite Missions, - Lunar and Martian Exploration, - Next Steps in Exploring Deep Space, - Space to promote Peace, - Space Traffic Management, - Knowledge Management in Space Activities, - Cost Effective Earth Observation Missions.

Events: Establishment of cooperation with national academies: The Royal Swedish Academy of Sciences (1985), the Austrian Academy of Sciences (1986, 1993), the Academy of Sciences of the Institute of France (1988, 2001), The Academy of Finland (1988), Indian Academy of Sciences (1990, 2007), The Royal Spanish Academy of Sciences (1989), German Academy of Sciences (1990), The Kingdom of Netherlands (1990), RSC: The Academies of Arts, Humanities and Sciences of Canada (1991), the U.S. National Academy of Sciences (1992, 2002), the U.S. National Academy of Engineering (1992, 2002), the Israel Academy of Sciences and Humanities (1994), Norwegian Academy of Science and Letters (1995), Chinese Academy of Sciences (1996, 2013), the Academy of Sciences of Turin (1997), the Australian Academy of Sciences (1998), The Royal Netherlands Academy of Arts and Sciences (1999), the Brazilian Academy of Sciences (2000), the U.S. National Institute of Medicine (2002) the Academy of Sciences of South Africa (ASSAf) (2011), the Royal Society of South Africa (2011), the Pontificia Academia Scientiarum (2012).

Publications: The journal of the Academy, Acta Astronautica (elevating to impact factor 4th position upon 64 scientific journals); IAA e-newsletter; Yearbook, Dictionaries and CD-ROM in 24 languages (last languages added Afrikaner and Swahili), Position Papers and Cosmic Studies (https://shop.iaaweb.org/), IAA Book Series on Small Satellite - Programs, Missions; IAA Book Series on Conference and Symposium Proceedings; IAA Book Series on Remote Sensing of the Earth System - Science, Technologies and Applications; Scientific Papers Data Base on the IAA Web site.

Members: Full and Corresponding Members (active: 1123) in four Trustee Sections; Honorary members (3); members in 81 countries.

- Africa: Algeria, Burkina Faso, Cameroon, Egypt, Ethiopia, Ivory Coast, Kenya, Libya, Morocco, Nigeria, Senegal, South Africa, Tunisia.
- Americas: Argentina, Bolivia, Brazil, Canada, Chile, Columbia, Cuba, Guatemala, Mexico, Peru, Uruguay, USA, Venezuela.
- Asia: Bahrain, Burma, China, India, Indonesia, Israel, Japan, Kazakhstan, Korea, Kuwait, Kyrgyz Republic, Malaysia, Mongolia, Pakistan, Saudi Arabia, Singapore, Sri Lanka, Syria, Thailand, Turkey, Vietnam.
- Europe: Armenia, Austria, Belarus, Belgium, Bulgaria, Croatia, Czech Rep., Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Macedonia, Netherlands, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom, Ukraine.
- Oceania: Australia, New Zealand.

Headquarters in Bern, Switzerland**, Secretariat:** 6 rue Galilée, 75116 Paris, France; Branches of Secretariat in Bangalore (India) and IAA Study Center in Beijing (China); Regional offices in Abuja (Nigeria), Tunis (Tunisia), Buea (Cameroon) and Nairobi (Kenya).

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Appendix H: The Economics of NEOs

THE ECONOMICS OF NEOS

Workshop Summary, NASA Research Park, Moffett Field, California, Sept 6&7, 2014.

NASA's Ames Research Center, in its role as partnerships lead for NASA asteroid redirect robotic missions and as a supporting Center for the Asteroid Grand Challenge, responded to increasing interest in near-Earth objects (NEOs) by holding a workshop entitled 'The Economics of NEOs' on the 6th and 7th of September 2014. The workshop was intended to serve as a catalyst for discussions and to foster collaborations between industry, academia and government. This document serves as a summary of the discussions which took place within three sessions and their respective table discussions; Session One: Background and Motivation; Session Two: Economics of NEOs; and Session Three: Policy and Legal Frameworks. This document is a collection of observations by individuals and does not express the consensus view of all participants; it does not express US Government or NASA policy.

Key Workshop Findings:

10. Greatsynergiesexistbetweenplanetarydefense,scientificresearch,spaceexploration, and commercial space activities—including mining of minerals and volatiles—that could be strengthened through public-private partnerships.
11. There is a need for a space-based telescope designed to be part of a broad survey detecting and characterizing asteroids, and for the benefit of all stakeholders in the NEO community.
12. There are a number of technology barriers—particularly relating to long-distance robotic mining and in-situ resource utilization—but many participants are confident they can be overcome in the near future with focused efforts.
13. Economicbarriersexistbecausetheperceivedandactualrisksforlong-termreturnson monetary investment are deemed high. However, private companies in the trade indicate near-term revenue streams on relevant products are already being actualized.
14. Certainhigh-net-worthindividualshavethenecessarycapitalandincentivetospendon legacy-building projects which include the prospect of mining NEOs.
15. AmbiguitiesinapplicableinternationallawneedstobeaddressedwithregardstoNEO activities. This is equally important whether or not such activity is scientific or commercial in nature.

16. Government space agencies, international regulatory bodies, private companies and academic institutions might work together closely on a long-term strategy regarding NEOs specifically, enabling the industry to grow in a stable, supporting environment.
17. The private sector could be more vocal about NEO activities with respect to desired reforms in applicable laws and policy as well as short-term investment opportunities.
18. Thedevelopmentofalegalandpolicyframeworkmayhelpenableacommercialspace mining industry.

Introduction

The 2013 Chelyabinsk meteor demonstrated that uncertainties still exist in our understanding of near-Earth objects (NEOs). Although the impact rate for dangerous asteroids is low, the consequences of such an event are severe. Over the past two decades, NASA has established a program which supports several projects to detect and research NEOs. However, further efforts are needed to effectively explore the scientific and technological means to detect, track, characterize, mitigate and communicate potential threats. Although asteroids are viewed as hazardous, they are also seen as objects of opportunity. Today multiple actors in the private sphere are seeking to mine these bodies for commercial purposes. The economics and regulatory questions that arise from such pursuits were at the core of the workshop: The Economics of NEOs.

Session 1: Background and Motivations

The motivations behind the interest in NEOs are many and varied. The first session of the workshop delved into these motivations and identified places where goals are aligned, and where there is significant project overlap. In no particular order, the five main motivators for the exploration of NEOs are: i) scientific exploration; ii) planetary defense; iii) resource extraction; iv) to provide material support and resources for missions beyond low Earth orbit (LEO); and v) to provide destinations for the human exploration of space. These are addressed accordingly.

<u>Scientific Exploration:</u> Astronomers were the first people to explore asteroids remotely and often used observatories funded by private philanthropists. Today, largely thanks to projects run by government and academia, science is still a motivation for missions to explore NEOs. Asteroids can teach us about the formation of the Solar System and the early history of the Earth and Moon. Hence, telescope surveys, in-situ analysis and sample return missions all continue to be of real interest to the scientific community.

<u>Planetary Defense:</u> While unlikely, an asteroid impacting Earth with devastating consequences poses a real danger—one which governments and the scientific community have begun to take seriously. Thus, programs have been created by NASA and other agencies to catalogue and track NEOs. These include the NASA Asteroid Grand Challenge and the NASA NEO Observations Program. Some of these programs have demonstrated increasing opportunities for participation by citizen- scientists in tracking and characterization.

<u>Resource Extraction:</u> Although typically relegated as ‘pure science fiction,’ the prospect of mining NEOs for minerals and volatiles—whether transported to Earth or for utilization in space—has begun to be featured in more serious terms. Key motivators include: i) profiting from the sale of valuable minerals back on Earth, ii) supplying a growing population with increasingly rare minerals; iii) protecting Earth’s environment; and iv) the creation of infrastructure that would support deep space missions and a financially viable space economy.

<u>Support for Missions Beyond Low Earth Orbit:</u> Earth’s gravity well makes any mission beyond LEO such an expensive endeavor that conference attendees felt it unlikely that we will ever establish a robust presence in deep space without changing the current paradigm. If asteroid materials could be mined and

processed, it would enable much lighter spacecraft to launch inexpensively and refuel, repair—and even one day be constructed— in space.

Human Exploration of Space: The NASA Asteroid Redirect Mission (ARM) suggests that an asteroid is seen as the agency's next destination for human space travel and the first destination beyond LEO since the Moon. In addition to providing a destination for the next beyond-LEO human spacecraft missions, such a mission will provide vital information on the makeup of asteroids and is intended to demonstrate techniques that could be used to deflect hazardous NEOs.

Session 2: Economics of NEOs

The second session focused on NEO activities by NASA and NEO prospective activities by commercial companies. Representatives from NASA and several private companies presented an overview of their projects and, in the case of the commercial players, presented business cases. The principal topics were: i) the need for comprehensive asteroid identification and characterization; ii) profitability in the short-, mid- and long-term; iii) the case for the sale of asteroid material on Earth and the case for the use of such materials in space; and iv) the case for initially targeting volatiles.

Asteroid Identification & Characterization: A combined effort to identify asteroid candidates which interest community would help prevent duplications of effort. The NEO arena would benefit from significantly more information about asteroids' location, size, and composition. Workshop attendees felt that ground- and space-based telescopes need to be built and used specifically for this purpose. If government has a scientific planetary defense interest, it might invest alongside a company with an interest in resource extraction. The partners could share the detection infrastructure and equipment. In this regard, the community as a whole might follow the example of one aspect of NASA's Asteroid Redirect Mission: the intention to "pursue a target of opportunity that benefits scientific and partnership interests, expanding our knowledge of small celestial bodies and enabling the mining of asteroid resources for commercial and exploration needs."[89]

Short-Term Profitability: As the private space industry matures, companies in all spheres are beginning to make real profit in space. The key for asteroid mining ventures is to begin realizing profit along the path to mining an asteroid because the market and infrastructure may develop slowly. Revenue obtained through developed intellectual property and other stepping stone projects can be used to fund a longer-term goal. Several companies claim already to be earning significant short-term profits. It was also noted that insurance policies can encourage nervous investors to begin supplying capital.

Medium-Term Profitability: Many players hope the government will play the role of "first customer". This was seen to be successful in the development of commercial aeronautics and, more recently, in the Commercial Cargo and Crew Program for transport to Low-Earth Orbit. While the demand for refueling stations in orbit doesn't currently exist, an administration like NASA might offer to purchase a specified quantity of a basic resource like water in space on a certain date for a set price. This would give investors more confidence in the medium-term profitability of the industry.

Long-Term Profitability: Commercial companies planning to exploit space-based resources have a

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[89] NASA, Asteroid Initiative Opportunities Forum – Update on Asteroid Redirect Mission (2014) *available at* http://www.nasa.gov/sites/default/files/files/AsteroidRedirectMission_Update_Panel.pdf.

common desire to extract and sell minerals from NEOs. Some plan to work with water. But water is not currently very valuable on Earth, and organizations hoping to sell asteroid resources back home are interested in rarer and more expensive minerals as well. Although some companies plan to pursue both markets, ultimately, there are two different approaches advocated within the industry. Some believe that true profitability lies in selling rare elements back on Earth, while others insist that this is not economically feasible and that the principal reason for extraterrestrial mining must be to support beyond-LEO travel. In each scenario, infrastructure, customers, and resources harvested would be different. There is currently a fierce debate as to which of these two paths is the most economically viable and there is no clear consensus within the community. Some of the pros and cons raised at the workshop are listed below.

Resource Extraction: Return to Earth

Pros:

- Asteroids have different elemental make-ups to the Earth's crust so we may find rare elements in abundance;
- We are running out of resources to support our expanding population; and
- Moving mining to asteroids will help create an environmentally pristine Earth.

Cons:

4. It will be very expensive to bring minerals back to Earth;
5. The fabled "platinum asteroid" is unlikely to exist;
6. We are not yet seriously running out of essential minerals; and
7. We still haven't explored the 70% of total mineral deposits under the oceans

Resource Extraction: Use in Space

Pros:

- It will be necessary to supply fuel and provide construction and repair services in space for a robust space industry to become economically viable;
- The Earth's gravity well makes launching materials, fuel, and parts very expensive;
- Supply depots in orbit and on asteroids and the Moon could make missions to other Solar System bodies much cheaper;
- The establishment of propellant depots at key locations in near Earth space would enable reusable transportation in space to become viable; and
- We must demonstrate that resources can be extracted and processed close to Earth before we begin trying to build self-sustaining communities on more distant bodies such as Mars.

Cons:

- There is currently no customer for resources in space;
- There are significant technology barriers for complex in-situ mineral processing; and
- There is no infrastructure or design standard to support this kind of system.

Water as First Target: A common theme was that water is the most feasible resource to target first. Water, and the elements from which it is comprised, are abundant, useful, and very expensive to launch from Earth. Extracting it from asteroids would allow it to be used for propulsion, water and oxygen for life, and various mineral processing schemes.

Government as First Customer: Since there is not currently a market for resource supply in space, it was suggested that the government might act as the first customer. By guaranteeing a price and quantity for purchase of water in space by a certain date, it would allow private companies to raise capital based on the concrete projected returns and thus jump- start the industry.

Session 3: Policy and Legal Frameworks

Session 3 focused on questions of national and international law, ownership rights and the role of policy makers. While it was generally agreed that current international treaties—principally the 1967 Outer Space Treaty and the 1984 Moon Agreement—are insufficient for the current environment there was little consensus on a path forward. Key questions involve i) the role of government, ii) the need for legal certainty, iii) whether to amend or rewrite current policy, iv) roles and responsibilities governments can assume to encourage the industry, and v) the need for industry leadership.

The Role of Government Legal Certainty: National and international governing bodies are in positions either to help birth the nascent asteroid mining economy or make it close to impossible for it to succeed. Participants felt that government policy might encourage business ventures by removing restrictions, granting tax incentives and by providing the security early investors need in the form of guaranteed business, insurance and public-private partnerships. However, if governments insist that comprehensive policy be enacted before any commercial activities involving asteroids takes place, it might result in a stillborn industry. A fundamental question raised about the role of the government is whether something needs to be considered forbidden unless it is expressly authorized.

Attendees sensed a mismatch between the pace of innovation and the government's ability to consider new legislation. In general, the business representatives at the workshop believed that if asteroid mining is not forbidden, then it should be considered legal. Some policy analysts and lawyers were more cautious however, advocating lobbying of lawmaking bodies and the creation of a robust commercial space policy before companies embark on major endeavors. Adding to the uncertainty is the fact that although the Outer Space Treaty doesn't explicitly prohibit exploitation of space resources, not all countries agree with this interpretation.

Legal Certainty: The question then becomes whether we need more legal certainty or whether the ambiguous legal environment is actually more conducive to a new commercial enterprise as policy can be written with real rather than hypothetical circumstances in mind.

Amend or Rewrite? This led to a discussion of the current international legal framework. Since we have a number of international treaties in place already, the subject of whether we can amend the old laws or whether we need to write completely new treaties needs to be broached. Either way, it is unclear what body would lead the push for change. Countries at the forefront of the issue might begin by creating domestic policy which others could follow until there is enough traction to begin tackling the big international treaties.

A Different Era: Current international space laws were written for a very different era. Treaties written in the 60s do not reflect the current entrepreneurial environment but rather Cold War-era geopolitical concerns. Furthermore, because of the pristine nature of the space environment itself, interpretation of the law often focuses on the restrictive elements of the wording, rather than that which enables the activities to proceed. This makes it difficult for organizations to know how to proceed.

Discussion of Possible Government Actions and Objectives: As demonstrated above, there is little consensus on how to proceed. Questions still to answer involve—among other things— the ambiguous legal environment, ownership rights and interpretation or amendment of the Outer Space Treaty, but it is unlikely many will be resolved soon. There are, however, initial steps governments might take to help this fledgling ecosystem today. Listed below are a number of specific governmental responsibilities and actions discussed at the workshop. These might help the NEO community succeed in an environment where there is little infrastructure, few existing customers and a sometimes ambiguous or outdated collection of national and international laws.

Possible government objectives:

- Enable development and success of industry;
- Nurture and support nascent industries;
- Focus on national programs which are outcome oriented;
- Regulate where necessary;
- Bear necessary costs that are too high for the fledgling industry; and
- Act as first customer to guarantee market in a new field.

Possible government actions:

- Provide geoscience information, e.g.mapping and analysis;
- Conduct research and development;
- Institute favorable property rights and mineral claim regimes;
- Adopt a “no taxation in space” policy during the industry’s infancy;
- Develop specific processes to deal with regulatory issues as they arise;
- Commit to purchasing services on a specific date for a specific price; and
- Allow private companies to use their communications capabilities.

<u>Industry Leadership:</u> To alleviate the fears of companies and investors, the workshop discussed the idea of a charismatic figure or organization that might fight for the vision of commercial space and help guarantee the future of the industry whichever of the above paths are followed. Some of the attendees went so far as to argue that legislation restricting our ability to explore and settle the universe is a crime against the future.

Conclusion

The Economics of NEOs workshop was an important and successful endeavor. Over 100 guests from across this emergent field attended, representing—among others—academia, the scientific community, international governments and aerospace agencies, commercial and industrial leaders, policy analysts and lawyers, all of whom are poised to play pivotal roles in the future of public and private space.

The quality of discussion allowed the attendees to isolate the most salient challenges and opportunities presented to the NEO community. Thanks to serious and thought-provoking presentations, questions, and table discussions, participants are better prepared to meet the upcoming challenges and opportunities head on.

Standing on the threshold of a completely new chapter of the space age – one in which planetary defense, solar system exploration, and resource utilization converge, participants of the economics of NEOs will no doubt play an important role in shaping its future.


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