International Academy of Astronautics

IAA- WAS0510
Space Mineral Resources: Challenges and Opportunities

Preliminary Findings and Recommendations for Heads of Space Agencies

To enable exploration and use of this new ocean and its new lands.

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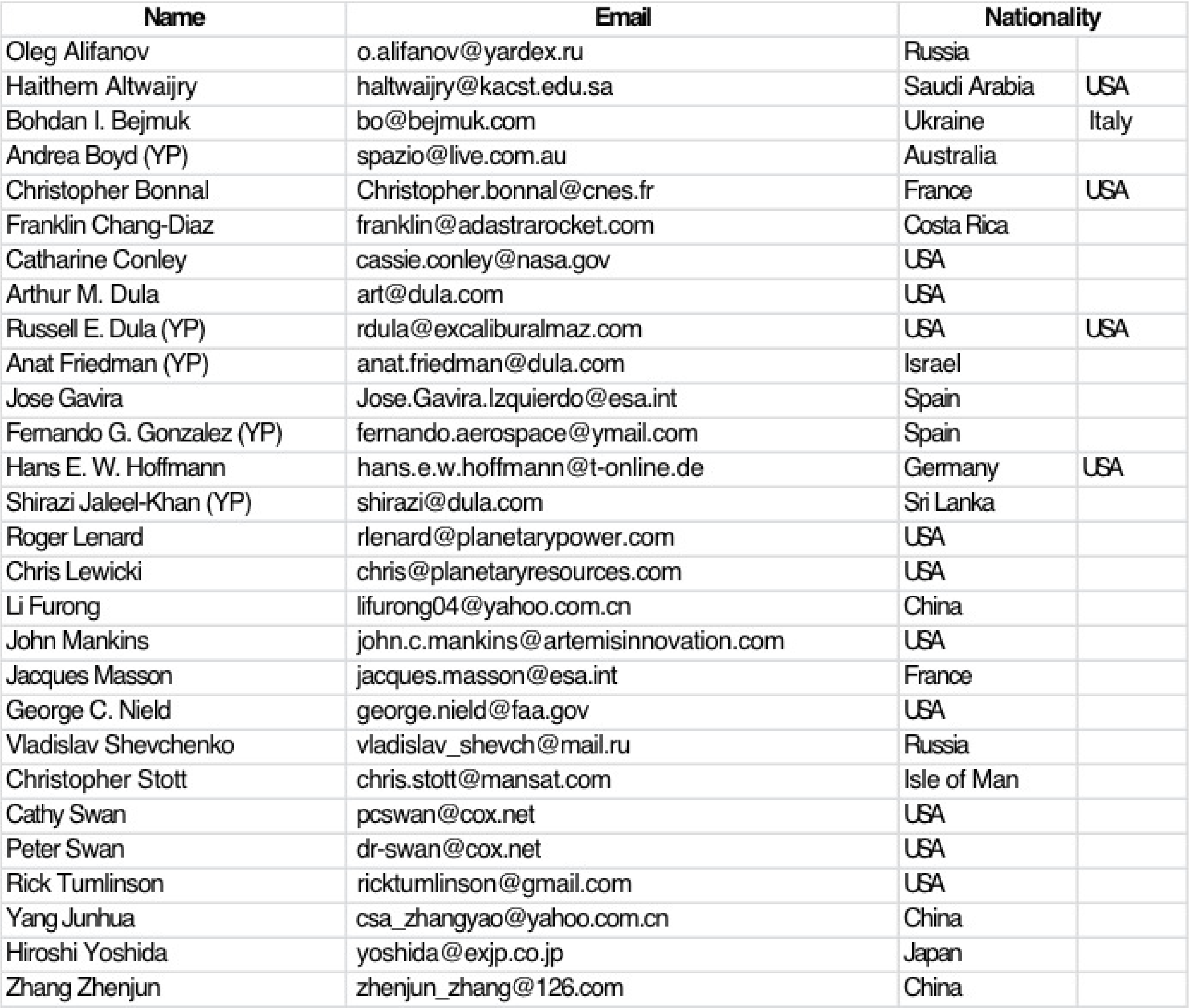

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Note: “YP” is “Young Professional”

GLOSSARY

CIL: Customary International Law

CJS: Corpus Juris Secundum (The Law of Outer Space)

OST: The 1974 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies

SMR: Space Mineral Resources

VC: The Vienna Convention (A treaty and resource considered the defining authority on the principles of treaty interpretation)

2. EXECUTIVE SUMMARY

The development of space mineral resources is a new commercial space endeavor for the benefit of humanity. In 2012, the IAA approved a broad study of the technology, economics, legal issues and policy aspects of identifying, obtaining, and using these resources. This study is now ending its first year and is near a final draft. The draft study presents several preliminary findings and recommendations for consideration by the IAA as topics for near term action to be taken by the heads of space agencies.
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 the Space Mineral Resource opportunity. The study will make specific recommendations for moving forward, and it will also provide a brief analysis of opportunities. This study is organized to provide technical information, policy and legal analysis, economic context and opportunity analysis, and recommended steps for moving forward.

3. INTRODUCTION

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 the historian H.G. Wells put it, is "the universe or nothing."

Data indicates Earth may be approaching a tipping point. According to new research, projections of catastrophe predicted by the Club of Rome[1] actually match current data indicating a high likelihood of environmental collapse by 2050, should current trends remain unchanged[2]. 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 of products 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 mineral endowment. While new technology offers hope by creating alternatives and increasing efficiency, 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"[3] – a metaphor for the use of the 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, the approach to leverage space resources defeats that projection, as so nicely described by Dr. O'Neil.

> "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...'"[4]

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 and 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.The commercial space mineral resource approach has been discussed for decades. 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, 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)[5].

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 ever before 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. To quote space pioneer Konstantin Tsiolkovsky,

> "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."[6]

This journey forward 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 creation of the large-scale structures imagined by science-fiction, enable 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." Clearly, expansion of human civilization into the universe is not a matter of "whether" but rather of "when," "how," and "by whom."

3.1 Overview - Situational Awareness

A clear understanding of Earth's current situation is necessary to evaluate the potential of space mineral resources for the benefit of humanity. Our entire species exists upon this single world, and its resources are finite; we do not truly exist beyond our terrestrial confines. Humanity is not yet a spacefaring species; we are a space visiting species.

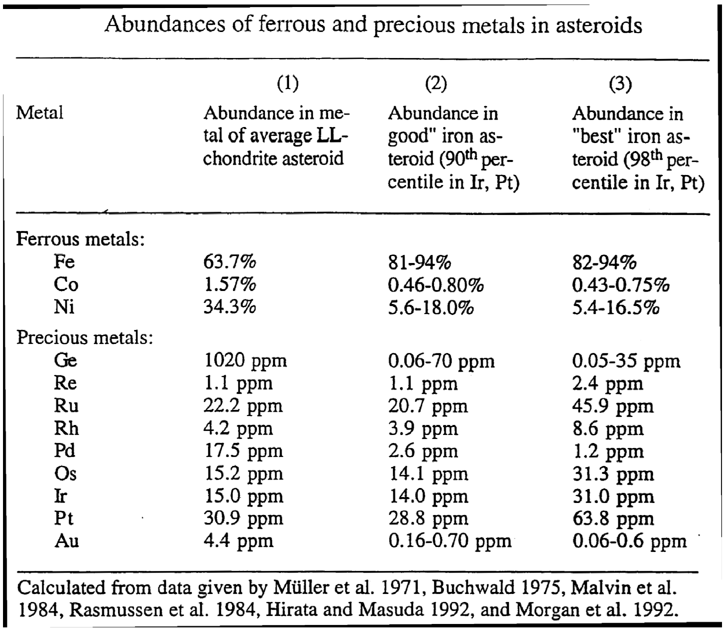
In more than a half century since the first orbital flight of Yuri Gagarin less than 700 humans have traveled, however briefly, to Earth orbit. The population of space has never been more than 15 in all those decades and no one has stayed more than two years. Only thirty humans have traveled as far as the moon, and only twelve have landed on its surface. None stayed. No one has yet traveled beyond the moon into the deep space between planets where the vast bounty of mineral resources exists.

Since 1950, the Earth's population has increased from 2 to 7 billion. Almost all this growth is in the population of less developed nations given that the more developed nations tend to have stable populations that tend to slightly decline as living standards rise.

The Earth's gross economic product in 2011 was approximately $70 trillion US dollars. For a population of about 7 billion people, this is around $10,000 USD per year per person. This economic benefit is not evenly distributed. Much of the Earth's economic wealth benefits the populations of a few nations. 40% of the world's population, which is about 2.8 billion people, have more than 96% of the world's wealth. This leaves 6% of the world's wealth for 4.2 billion people, 60% of humanity. This economic gap is getting wider.

Humans are innately driven to better their lot and the lots of their children. If everyone wants to live in a sustainable economy with a high standard of living, then 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. Opening the resources of space will not only change our lives; it will change our destiny. Use of these 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.

Generally, metal rich asteroids have a range of compositions, but 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.



Abundances of ferrous and precious metals in asteroids

Metal	(1) Abundance in metal of average LL-chondrite asteroid	(2) Abundance in good" iron asteroid (90th percentile in Ir, Pt)	(3) Abundance in "best" iron asteroid (98th percentile in Ir, Pt)
Ferrous metals:			
Fe	63.7%	81-94%	82-94%
Co	1.57%	0.46-0.80%	0.43-0.75%
Ni	34.3%	5.6-18.0%	5.4-16.5%
Precious metals:			
Ge	1020 ppm	0.06-70 ppm	0.05-35 ppm
Re	1.1 ppm	1.1 ppm	2.4 ppm
Ru	22.2 ppm	20.7 ppm	45.9 ppm
Rh	4.2 ppm	3.9 ppm	8.6 ppm
Pd	17.5 ppm	2.6 ppm	1.2 ppm
Os	15.2 ppm	14.1 ppm	31.3 ppm
Ir	15.0 ppm	14.0 ppm	31.0 ppm
Pt	30.9 ppm	28.8 ppm	63.8 ppm
Au	4.4 ppm	0.16-0.70 ppm	0.06-0.6 ppm

Calculated from data given by Müller et al. 1971, Buchwald 1975, Malvin et al. 1984, Rasmussen et al. 1984, Hirata and Masuda 1992, and Morgan et al. 1992.

Figure 1 Precious metal abundances for LL chondrites and iron asteroids.

Given the facts above, 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. 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. 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.*** *[emphasis added] 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."*[7]

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.

Situational awareness is extremely important in this virgin frontier. The number of spacecraft missions to the Moon, Mars and near-Earth asteroids (NEAs) is growing, yet more discoveries will be needed. This will provide a dual benefit commercially as well as for planetary protection. This study will generally describe what is up there and what can be done with it. Due to the exponential abundance of SMR, we could even eventually stop mining the surface of Earth – a long-term vision with an environmental payoff.

> *"NEAs contain a variety of raw materials that could be harvested, including useful substances such as iron, rock, water, carbon, nitrogen, semiconductor and platinum group metals, and trapped gasses such as carbon dioxide and ammonia. These resources can be utilized for a variety of purposes, including the manufacture of radiation shielding and spacecraft propellant, without needing to expend the tremendous energy required to launch the raw materials into space from Earth or another gravity well (such as the Moon or Mars). Harnessing these resources will require extensive infrastructure development, however the first steps are to identify available resources and develop utilization capabilities. That will require scientific study, the ability to have humans operate effectively and safely in the vicinities of NEAs and on their surfaces for extended periods of time, and the capability to modify NEA orbits. NEA resource utilization is clearly synergistic with solar system science, planetary defense, and human exploration."*[8]

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 900 each year, but will 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; currently, none have orbits that threaten Earth over the next few centuries. Smaller NEAs still can wreak havoc on a regional scale, and a thriving space industry seeking them for their resource value could provide the on-going funding required to identify and characterize as many as possible.

3.2 The International Academy of Astronautics 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 the Space Mineral Resource opportunity. The study will make specific recommendations for moving forward, and it will also provide a brief analysis of opportunities.

Specific questions that will be answered by the final study include:

- What are people’s opinions in society regarding the legal and policy options?
- What the primary challenges are to getting SMU mature (legal, policy & economic)?
- What are the technical challenges to state of the art?
- What are the recommendations for action?
- What are people (including NASA and the other space agencies) doing now about it?
- Of the people trying to do this, what are their roadmaps to get there?

This study is organized to provide technical information, policy and legal analysis, economic context and opportunity analysis, and recommended steps for moving forward. It is divided into basic sections based on architectures, systems, technologies, law and policy, and economic analysis. Appendices will accompany the finished study to include additional related information in order to facilitate a deeper understanding of core issues & opportunities.

Technical information related to Space Mineral Resources disclosed in this report including 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. Finally, the full study will offer an international roadmap showing pathways forward.

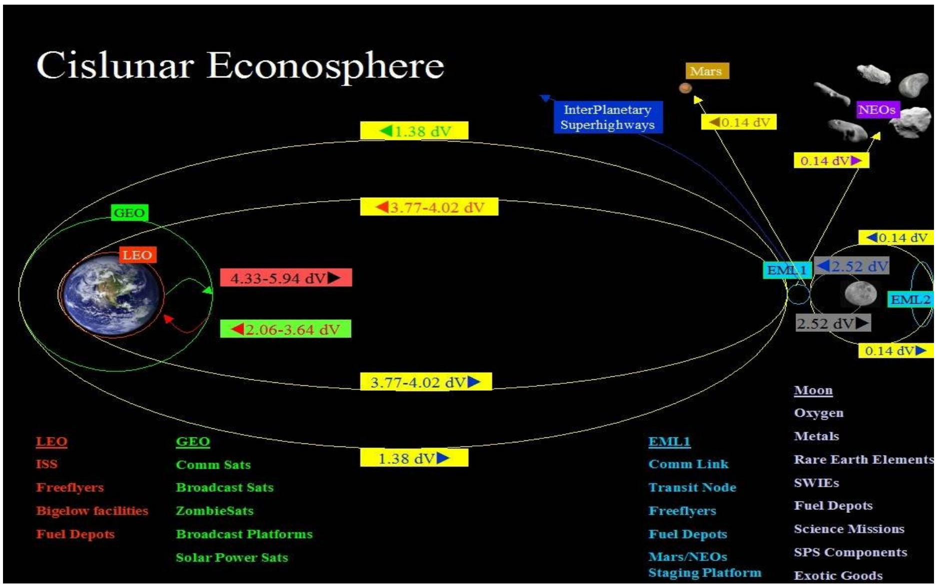


Figure 2. Cislunar econosphere showing delta-V and products.

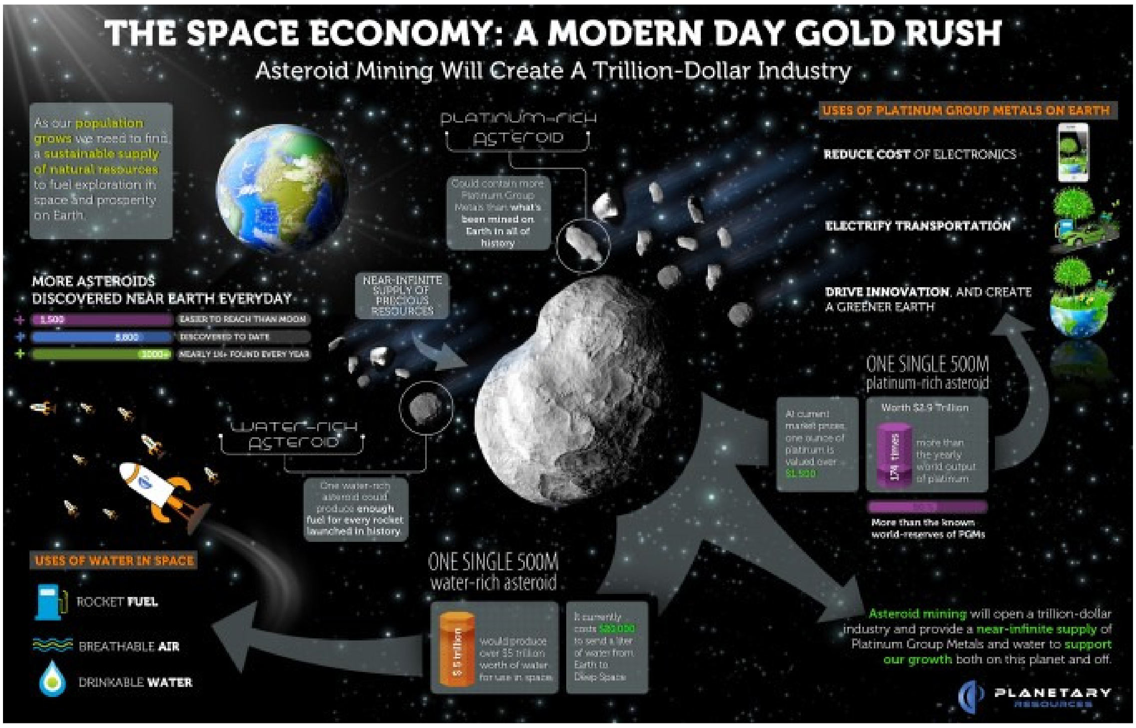


Figure 3. Future space economy scenarios are enabled by asteroid SMR (courtesy Planetary Resources).

4. SMR SYSTEMS CONCEPTS

A wide array of mining and mineral extraction technology exists 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.

This chapter will discuss systems concepts for SMR and summarize technical content. It will be an attempt to organize these concepts into categories based on end uses, type or class of resource, and technology. The full study will briefly review the results and status of prior art, with technology and risk assessment covered in Section 4.0 in more detail.

4.1 Design Reference Missions

"Design Reference Missions" (DRMs) are hypotheticals used to establish the methodologies of potential space missions. Missions to the Moon, for example, might assume a single rocket like the Saturn V used in the U.S. Apollo program, or they could be based on multiple launches of smaller payloads that are assembled in Earth orbit, in 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.

4.2 DRMs based on Government Sponsored Human Exploration

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 is that it will open new avenues for the exploration and utilization of space. In-situ utilization will allow for efficient distribution of fuel and materials to explorers, and it will increase drastically lower the time and money costs involved in the construction, utilization, and development of space vehicles and assets.

In the late 1970's a well-funded NASA study lead by General Dynamics examined in detail how to build a large-scale orbiting solar power system using lunar resources. The model assumed the operation of a 400-man lunar base for the purpose of mining local resources for the construction of a series of 100,000 metric ton LEO power satellite stations. Note that the lunar base design for this study was minimal. However, the design of lunar manufacturing facilities, and technical discussion of the underlying refining and fabrication capability was extensive. This study stands as the most detailed design of a lunar manufacturing facility done to date.

4.3 DRMs based on 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 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 well within sight of the US$55 million price of a ton of gold on Earth. In sum, 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 the scarcity of the environment. However, this added value is lost once the object is brought back to Earth. DRMs 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.

DRMs based on 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 on commercial or government pursuits. These DRMs can be sorted on two axes: the in-space destination, and the type of materials to be delivered.

4.3.1 *Near-Earth Destinations*

The space locations near Earth with the most activity today are low Earth orbits (LEO) 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 an attractive initial destination. In addition, to move asteroidal materials from a high orbit where NEAs will arrive down to LEO requires effort to remove orbital energy, making 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.

Destinations with far less current activity, but with the potential for growth, include the Lagrangian points in the Earth-Moon system and the Earth-Sun system. These are balance points where spacecraft can maintain position with minimal expenditures of station-keeping propellant. The balance points L1 and L2 in the Earth-Moon system, for example, are located on a line extending out from the Earth. L1 is about 84% of the distance to the Moon, located about 60,000 km above the near side, and L2 lies beyond the Moon's far side by the similar distance. As the Moon revolves around Earth, spacecraft in L1 and L2 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.

The Earth-Sun system also has Lagrange points. Earth-Sun L1 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 L2 – which has 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.

Finally, lunar orbit 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 L1 point where NEA processing would deliver propellant useful on both routes. Taken together, the destinations and the markets described in Section 6.3.1of the final study will suggest the primary Design Reference Missions for Space-Based Markets described below:

4.3.2 *DRM L1*

Earth-Moon L1 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 and object is in Earth's gravity well, the less energy is required to reach that location from the orbit of a NEA; this favors EM L1 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, L1 offers a unique opportunity to service many inclinations in Earth orbit without the usual plane change penalty. This makes it a very valuable and unique location for inbound as well as outbound orbital transfer. Indeed, an L1 traffic control authority will be an early policy requirement to minimize scheduling and operational conflicts.

4.3.3 *DRM GEO*

This location is closest to the largest existing in-space market for asteroid resources, and 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 the active satellites below. While it takes more energy to reach GEO than L1 from a NEA orbit, this is offset to an unknown degree by the fact it is easier to reach from the Earth itself.

4.3.4 *DRM Lunar Orbit*

This is the least likely location to process asteroid material. First, it places processed asteroid materials in the Moon's gravity well restricting their mobility. In addition, the construction of large-scale industrial, observation or communication platforms in The Lunar Orbit has limited commercial use; 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 L1 than from a fixed lunar orbit. In addition, the instability of Lunar Orbit due to gravitational anomalies on the lunar surface makes its long-term use hazardous.

4.4 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, and so on. Longer term markets could include lower value materials.

Long-term terrestrial markets could include: Industrial products & 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 prior research for potential products made in space & returned to Earth. Many of these could be reevaluated for SMR contribution.

4.5 Recent Commercial Interests in SMR

Within the last decade, a number of private initiatives have surfaced promoting private space exploration and development. A partial list of companies interested in SMR is below

List of commercial lunar development companies
- Golden Spike
- Shackleton Energy Co
- Moon Express
- Excalibur Almaz
- Bigelow Aerospace

List of asteroid development companies
- Planetary Resources Inc
- Deep Space Industries
- Excalibur Exploration

List of commercial Mars development companies
- SpaceX

- Inspiration Mars
- Mars ONE

Investment in these companies by members of the Forbes Billionaire list is becoming increasingly fashionable. The list of six space-investing Billionaires (as counted by Forbes) in 2011[9] 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 1. Billionaire space investors in 2013[10].

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 Lansdorple's Mars One one-way mission has already exceeded 200,000 people demonstrating that risk preferences for human Mars exploration are loosening[11].

4.5.1 SMR Economic Assessment

Long-term customers for SMR could include users in space as well as on Earth. It is the purpose of this section to develop then use economic methods in order to estimate the value of SMR commodities in both situations. While a thorough economic analysis is impossible without access to full information, there is sufficient current information 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 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. In general, asteroid platinum-group metals (PGMs) and base metals have very high market certainty when considered for terrestrial commodity markets, but suffer from lower prices than those associated with in-space destinations, as well as strict volume or throughput limits (small increases in market volume can cause prices to collapse – a common problem faced by Earth's mining industry). In comparison, space-based propellants derived from asteroid or Moon/Mars water deposits have low market certainty, but 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 will be simply done by examining current price and quantity information from existing exchanges, the results of which will be used for feasibility analysis described later. Due to its novelty and importance, a quantitative in-space market modeling approach will be developed in a lot more detail below.

4.5.1.1 Modeling SMR Demand Scenarios

The evolutionary path of space markets can be predicted and modeled. Markets on Earth don't evolve in a vacuum. They enable each other, and are simply a function of capabilities, technology and infrastructure. Markets for space resources are likely to follow similar paths to terrestrial analogs, particularly for the energy, mining and manufacturing. There is much to be learned from terrestrial industrial examples, and these lessons can be utilized to illuminate a feasible path forward as humanity expands into its next frontier. Examples include transportation fuels, structural and precious metals, industrial and residential construction, mining and agriculture, entertainment and tourism.

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 either 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. Understanding how the mining and energy industry work from a mathematical perspective can illuminate future opportunities and help predict the value of SMR composition, timing and location.

What is desperately needed is a worldwide market-based vision for moving upward into the next frontier in an economically sustainable fashion. This can start by making guesses (models) about the nature & behavior of emerging and potential markets. 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 feasible within a given time frame. An important goal or outcome would be generation of sufficient information to inform investment decisions as well as the timing of new space product & service startups. Many of today's space commercialization concepts are premature. Sadly, good ideas that die on the vine due to lack of capital (or by providing products or services for markets that don't exist yet) could flourish under more mature conditions. Identifying boundary layers, factors or metrics to "keep an eye on" can help with synchronizing timing and opportunity management.

4.5.1.2 A Space Infrastructure Development 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 developed a Space Infrastructure Development Framework which 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 on 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, thus creating 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 and processing operations. One important "background reference" for estimating the future impact and cost of these elements lies within the engineering, cost and operations experience of NASA, which is a large-scale human spaceflight organization with sufficient openness to understand how it operates and makes decisions. The NASA budget and programmatic experience can serve as an important meter stick against which to measure or estimate private space investment.

4.5.1.3 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 and NEOs, and eventually grow to millions of people across the Solar System. A space infrastructure development framework is modeled, positing 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 analysis 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 in the asteroids in varying conditions and concentrations, including recently discovered high-grade deposits at the lunar poles. 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 for many of these low-energy transfer opportunities there can be 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 on human consumers could also be later 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.

4.5.1.4 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 because 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 will 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, nor would it require them to live out the remainder of their lives there. 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, then into a gradual geometric increase in later periods due to the assumed increasing use of SMR thus colony 'independence' from terrestrial constraints. One way to envision or understand this model is that presently there is at present only one real contender for deep space exploration – the Chinese government (while Russia could also be included, NASA has clearly taken itself out of the game). 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 them succeeding is the inverse of the number of contenders. It is also likely that in the end some of the current actors will merge into a larger team than have been created to date for the NASA Commercial Crew and Cargo or Google Lunar-X Prize. As this series of estimates expands out to the 5th period, 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 the larger framework to conceptualize the deep space infrastructure and the economy that will demand it, and serves as a point of departure for calculating the engineering and technology requirements to serve that future potential human population.

4.5.1.5 Life Cycle Cost in a Developing Solar System

Thanks to an all-expendable paradigm, spacecraft development and launch costs are currently a function of distance or energy. For launch, this is due to the exponential decrease in payload as you get higher in the vehicle stack. For spacecraft, this is due to communication complexity (delay and distance), required autonomy, environmental hostility and the need for high reliability. All of these factors are mitigated by having humans nearby. 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. Reusability can linearize the cost equation, decoupling it from the rocket equation, and allows capital to be more effectively employed. All one needs is a series of one or more fuel stops.
The high cost of space access is actually enabling for SMR. Indeed, it is the key to pricing models for SMR. The ability to sell items on the lunar surface to a customer for more than $1,000k/kg, or in LEO for $10k/kg makes SMR appear to be a really good idea. If space access became very low cost, why not export everything to space from Earth?

4.5.1.6 Feasibility Analysis: Comparing Costs and Revenues

Sustainable development of solar system resources will require identifying profitable conditions for lunar or asteroid mining. An integrated technical-economic approach can become a useful tool for identifying and bounding feasible regions for future private investment in space resources, and has successfully been applied to the lunar ice mining case[12]. Objectives of SMR technical analysis must include examining asteroid mining in terms of means, methods, and systems. Economic analysis will build upon those results by adding a layer of estimated development, production and operations costs for various scenarios or use cases, then comparing the costs at various points within the life cycle to a market and pricing model of expected consumer behavior.

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. Context is important – commercial asteroid mining will depend on a robust set of future capabilities including a Venus orbit NEO observatory, commercial transport for crew and cargo, and an Earth-Moon Lagrange Points (EMLP) propellant depot and mission staging platform, as well as other infrastructure nodes to deliver water and other products to customers ranging from LEO to Mars.

An analytical assessment process can be used to determine if identified asteroid mining business cases are viable. Economic modeling tools can create a set of point estimates that define a feasible region in market, cost and technical space using commercial investment standards. Technical and architectural parameters can generate a systems-level supply function, which can drive a detailed cost model. Starting with a conservative cost basis for spacecraft systems and components, a life cycle costing layer can be added to account for launch, operations and maintenance choices. A separate demand function can be created using terrestrial metals data combined with projected in-space products and customers. Equilibrium point estimates can result from mapping variations in supply and demand assumptions to illuminating feasible regions that would normally attract commercial investment under terrestrial conditions and risk preferences.

4.5.1.7 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 this 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 feedstocks such as scavenged orbital debris or asteroidal resources and will therefore contribute to the emergence of a larger economy. Markets and customer profiles are the foundation of the business model, and will form a key element of this paper. Anticipated customers could include: Space habitats, stations and industrial facilities; Building large beams in LEO or geostationary orbit to anchor growing aggregates for communication or remote sensing; Components for space solar power systems; Key elements of human solar system exploration systems such as radiation shielding; and, repair or replacement items for other damaged infrastructure.

Technology for in-space additive manufacturing and robotic assembly will enable many new commercial markets and serving NASA's vision, 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, even enabling in-space manufacturing of high-mass space solar power system elements (structural support and heavy mechanisms). If methods for extrusion of tubing in space are developed, radiators and other fluidic components could be manufactured using in-situ resources. Chemical vapor deposition of metal tanks and other complex closed fluid handling shapes could be enabled by the Carbonyl iron and nickel processes. If thin film deposition in microgravity and the natural vacuum of space is perfected (e.g. finishing the work started by the wake shield facility), automated space manufacturing of solar cells, sensors (thermal, mechanical, etc.), adaptive optics and electronic components would become enabled. Adding lithographic techniques would enable the potential for semiconductors and other nanotechnology systems to be manufactured without today's required environmental containment systems. Access to square kilometers of 25 Kelvin cryogenic, ultra-high vacuum environments (such as found at the lunar poles) could enable breakthroughs in science, technology or manufacturing due to the current high cost of creating similar features in labs on Earth. Large-scale space manufacturing will take advantage of different scaling laws and fundamental limits of physics, in the longer-term enabling the reforming of asteroids into G.K. O'Neil-style space colonies. Novel structural designs that could never be built in 1-g will be enabled, such as gossamer antennas and kilometer-long connecting beams.

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 current International Space Station offers a rich set of well-documented examples of how to do construction and assembly in microgravity. Lessons learned can inform mathematical models of the maximum buildup rates for more advanced infrastructure, such as a transportation-logistics node and propellant depot at L1. Combining manufacturing with assembly will enable more complex systems to be made in space, creating a source for on-demand tools, parts and other equipment enabling public and private space stations, hotels and commercial facilities to become within reach. An exponential decrease in dependency on Earth will follow, reducing launch mass and costs for Moon, Mars, and asteroid missions. New aerospace businesses, such as space-based solar power and low-cost private hotels will be enabled. Manufacturing capabilities on planetary outposts will depend on SMR for their input feedstocks.

4.6 Material (Ores) Acquisition

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.

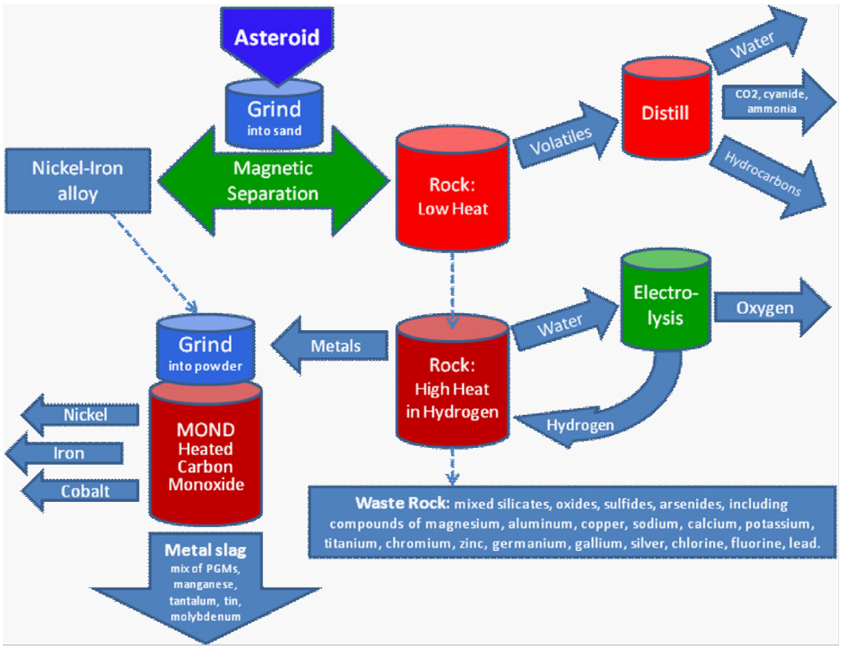
The alternative is to move raw asteroid material into a parking orbit near Earth or directly to Earth, either by moving an entire small NEA (one to ten meters diameter) or by collecting parts of a larger NEA and delivering that subsample. Small NEAs by their very nature are difficult to spot from Earth, 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.

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 similar gravity. Example mining systems are shown below. 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.

4.7 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 likely will 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 outputs 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 5. Asteroid material processing options and products (courtesy Deep Space Industries).

The circuit above could also extract metal from lunar soil, given the eons of bombardment of asteroidal materials onto the Moon also extract metal from lunar soil, given the eons of bomasteroidal composition by mass). 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.

4.8 Summary Evaluation of SMR Systems Types Examined

Classification of SMR systems by type or class can help identify uses, critical technologies and supporting systems. A commodity-based approach is first offered to frame customers and uses. Next, a geologic context is offered to highlight differences in each class of space resource. The role of orbital dynamics is evaluated, especially with regard to the tradeoff between time and energy. Finally, the role of exploration is placed within its proper context, as a supporting activity to expand the inventory of valuable resource targets.

An economic commodity perspective will also be offered for the evaluation of SMR. This viewpoint illustrates both the terrestrial industrial technology needed to create these products, as well as framing the potential customers for SMR. Commodities are openly traded and standardized products such as .99 or .999 purity copper or gold, but could also include other novel products that are so ubiquitous that they become standard products producible from most SMR sources and driving a standard market price at many destinations.

5. SMR SUPPORTING SYSTEMS

Supporting systems for SMR should be based on 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. For example, most private entrepreneurs consider it inefficient that NASA is entertaining that a $115 billion investment in the International Space Station be discarded. Examples of this type of wasteful thinking abound starting with scrapping the Apollo Saturn launch vehicle factory, not using the Skylab Reboost Module to retain the first US space station, and the cancellation of the Space Launch Initiative (a well-funded program to build a timely replacement for the aging orbiter that was shut down in 2002). 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. Design for space transportation system reuse as well as maintenance will sharply reduce systems reliability requirements and therefore costs, 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 ultimate objective should be development of an integrated transportation infrastructure designed for routine, inexpensive, and daily transportation to GEO and beyond; and return.

5.1 Earth-to-Orbit Transportation

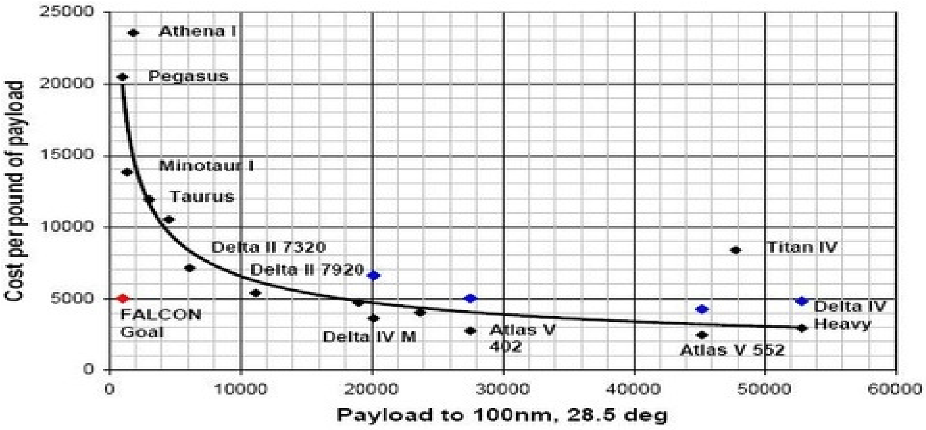


Figure 2. Launch Costs of Common Space Launch Systems

Figure 6. Earth to orbit transportation cost range.

The expendable Earth-to-Orbit (ETO) approach got the US to the Moon. However, its cost was very high due to risk and complexity. No replacement for the Saturn 1C stage has yet been reproduced by a US launch vehicle manufacturer, and cost estimates for the nearest current equivalent, Ares 5, remain in the mid-billions. There may be a better approach – one that demonstrates an on-orbit critical SMR capability – refueling from a terrestrially-supplied propellant depot. Heavy lift launch can be replaced by refueling and on orbit assembly. Studies have shown a significant performance increase with on-orbit operations and refueling (see Figure below).

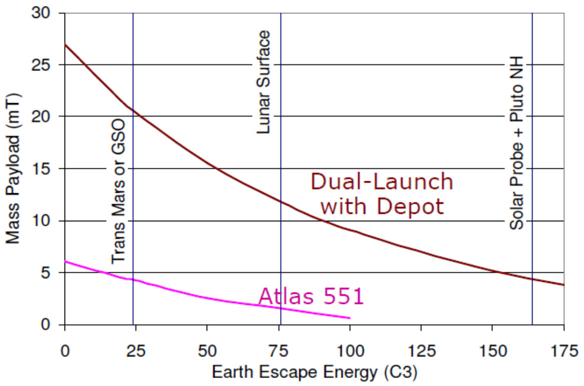


Figure 7. Significant LV performance increases due to dual launch with depot[13].

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.

However, enabling heavier payloads or lowering costs solves only part of the problem. One of the fundamental constraints of space launch is not only launch mass but also payload faring size. 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 ISS would not have been launchable in its current configuration using a single vehicle.

5.2 In-Space Transportation

Excess transportation capability for Moon-Mars space access is within easy reach should currently expendable systems start to be refueled and reused. The relevant example is the Centaur upper stage, which is currently used once before it is parked or discarded. Over 100 Centaurs remain in orbit, waiting for a propellant source. Extensive published work maps the technology demonstration paths to a fully reusable Centaur. 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.

5.3 Future Spacelift Infrastructure

A recent IAA study resulted in "Space Elevators seem Feasible![14]" Although the development of the tether material is currently at a TRL level of 1 or 2, the potential is remarkable and worth projecting. When the space elevator is operational, the infrastructure would include up to five pairs of space elevators around the globe. Each would provide daily, routine, and safe delivery of 14 metric tons of customer payload to GEO. The paradigm of expendable space flight vehicles is eliminated by a robust capability that can not only deliver over 5,000 metric tons to GEO per year; but, can bring "product" back to the surface of the Earth similar to \train or shipborne approaches. The option of a design reference mission should be developed looking at bringing space minerals back to the Apex Anchor of the space elevator [altitude – 100,000 km).

6. TECHNOLOGY READINESS AND RISK ASSESSMENT

Technology and risk are intimately connected. Technological investment is generally seen as a way to "buy off" or reduce system, component and process risk. Considering this, it is important to remember that the Apollo Program provides proof that new technology is not actually a requirement for human space access. It is neither necessary nor sufficient. Yet, the lack of technology has become a new excuse for program failure. Indeed, advancing technologies have become the rationale for many elements of NASA's budget. However, finishing a new technology is disruptive to 'business as usual' and is often inhibited by vested interests within the rival NASA centers. This institutionalizes conflict within a government bureaucracy by creating vested interests at odds with each other, while orphaning many promising leads. That said, the growing library of half-finished aerospace technology may have a silver lining in that is will perhaps enable commercial space enterprise. For example, the TransHab technology purchased from NASA by Robert Bigelow has found new life and is leading to new innovations in Bigelow's hands.

The same process and opportunity applies to risk. Drawing larger boundaries around aerospace risk profiles yields a startling insight: Programmatic risk is responsible for most space agency failures. Extensive effort is put into minimizing architectural, systems or component risk. Mission success depends on a low probability of failure. However, the huge price tags and long lead times needed to ensure a "low risk" human lunar mission (e.g. the Constellation Program) end up canceling one human lunar return program after another.

7. SMR POLICY, LEGAL AND OTHER CONSIDERATIONS

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 outright confusion and blatant misconception. Of these problems, the largest is the confusion surrounding the use and extraction of mineral resources from space. This uncertainty has left many pondering the legality of privately harvesting the mineral bounty of space and whether or not it can even be legally harvested. However, a thorough analysis will 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.

7.1 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. 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. COPUOS has seventy-four member states, and it has facilitated nearly all major space agreements. [15] COPUOS was a key player in the development of the *CJS*, [16] and is still relevant today. However, the topic of space law is becoming increasingly contentious as individual nations seek to develop and expand space law, and its many ambiguities, in different directions thereby increasing tensions.

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.”[17] Thus, space law itself is generally derived from three sources: international agreement, customary international law, and domestic legislation. 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; but, they have fallen short of providing a framework that fits perfectly.

7.2 Treaties Concerning Space Mineral Resources

Treaties comprise the majority of international space law. One treaty in particular is the most relevant when discussing space mineral resources: the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (hereinafter Outer Space Treaty or OST).This treaty provides both confusion and clarity on the subject, and deserves immediate attention.

The present *CJS* has been shaped and informed almost entirely by treaty. The field is relatively 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. [18] 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. [19, 20] 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,” and that “every treaty in force is binding upon the parties to it and must be performed by them in good faith.” [21] 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. [22] In the event that the rules of the Vienna Convention cannot resolve an ambiguity, the International Court of Justice can be employed by the parties to resolve the issue 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. [23]

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. [24] 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[25] – the *CJS* is no exception.

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,” that outer space “shall be the province of mankind,” 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,” and that “[s]tates party to the treaty shall bear international responsibility for national activities in outer space, including the moon and other celestial bodies.” The net effect of these provisions is that some scholars feel this requires 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, regardless of their participation in space activities. 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.” This, however, is referring to the claim of new physical territory, and it profoundly differs from the terrestrial practice of claiming new territories recognized by international law and practiced throughout all of human history. It is now generally accepted that claiming areas, such as claiming ownership of land on the moon, is against both the OST and customary international law. Nothing in the OST, however, prohibits commercial use and private development of space resources. For example, every State that has engaged in space activity has already appropriated certain space based resources for their own scientific and non-scientific uses. Resources such as solar winds, light, and mineral resources, including Moon rocks, are all routinely utilized in commercial actions.

7.3 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; and, the International Court of Justice is generally considered the first authority in defining CIL. While CIL specific to space is relatively sparse within the *CJS*, it nonetheless exists and defines certain parameters of acceptable conduct. [26] Also, it is tempting to disregard CIL given that it is so spare and relatively underdeveloped within the *CJS*. However, it is important to discuss CIL because now is the time to begin establishing the norms and practices that will drive SMR for the foreseeable future. By being mindful of how CIL forms and changes, present actors are better equipped to act prudently so that the resulting norms of international law will reflect wisdom and thoughtfulness.

CIL can generally be seen as a horizontal system in which states, [27] as putatively equal sovereigns, [28] come together and, through the practices and expectations of the large majority, form a body of law that is binding upon all. [29] 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.

CIL is considered binding upon all parties and its obligations are universal. CIL consists of two elements: general patterns of practice or behavior and general patterns of legal expectations or *Opinio Juris*. [30] 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. However, exceptions do exist, and CIL can form around specific situations, parties, or even geographical areas. 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. [31] Though many sources declared that only states may participate in the formation of these norms, a modern trend is the recognition that entities other than states can, and always have, helped create CIL.

The prong of general patterns of practice is especially important in understanding the CIL within the *CJS*. Increasingly, private actors front a presence 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 under the authority of state bodies as well (see Vienna Convention, re: states' responsibilities for it's citizens). 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, 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. The *Opinio 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, as only a select few are in a position to actually reach outer space.

With both prongs of CIL accepted generally, even if not universally, a new rule can then emerge. [32] 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 parties agree otherwise, a treaty will supersede a prior inconsistent rule of CIL. Other sources submit that CIL is formed from the general patterns of all mankind, and its universal nature cannot be trumped. 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. 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 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.

7.3.1. Analysis and Explanation of why Resource Extraction is Permissible

The first step in understanding why resource extraction is permissible under international law is to understand the language and definitions used in constructing the *CJS*. The most important thing to do is understand the scope of the *CJS* and to understand where it does and does not apply.

7.3.1.1 ***Scope of the OST***

The universe, being the sum of all creation, is unimaginably vast in its potential and variation. The legal size of the universe, according to the *CJS*, is only slightly less infinite because the earth is the sole area upon which the *CJS* does not control due to the wording of the OST. Turning once more to the Vienna Convention, one remembers that treaties are to be interpreted "in good faith in accordance with the ordinary meaning to be given to the terms of the treaty in their context and in the light of its object and purpose."

First, the *CJS's primary focus* seems to be mostly focus on maintaining the free, peaceful, and productive use of space. Thus, any definition should align with those goals. The OST refers to "the moon and other celestial bodies," as being "not subject to national appropriation or claim of sovereignity" but "for the benefit of all mankind."A bit more light is shed by Article I of the 1979 Moon Treaty which states that

> 1. The provisions of this Agreement relating to the Moon shall also apply to other celestial bodies within the solar system, other than the Earth, except insofar as specific legal norms enter into force with respect to any of these celestial bodies.
>
> 2. For the purposes of this Agreement reference to the Moon shall include orbits around or other trajectories to or around it.
>
> 3. This Agreement does not apply to extraterrestrial materials which reach the surface of the Earth by natural means.

While it is certainly true that the Moon Treaty is not controlling due to its near total failure, it might be useful as supplemental evidence of the meaning behind both "appropriation" and "benefit"" as it is used in the *CJS*. Because the meaning of treaties can be dynamic in the face of "any relevant rules of international law applicable in the relations between the parties" it is perhaps probable that the rejection of the Moon Treaty illuminates the subsequent and dynamic practices and understandings surrounding these applications to SMR.

It is not necessary that a perfect definition be created, merely one that fits properly within the legal landscape of the *CJS*. Indeed, nations will very much be forced into defining certain aspects of the *CJS.* The Vienna Convention and CIL require that nations employ domestic legislation without delay or impediment to enable and support binding international law. Thus, the development of the *CJS* and the resolution of its definitional ambiguities should stem, at least partly, from domestic interpretations.

7.3.1.2 Space Policy: Where Treaty Law Stops, Policy Begins

The Policy of the United States, and others, is that they will not participate in the United Nations Convention on the Law of the Sea (UNCLOS) or the Moon Treaty as those agreements seek to systematically prohibit the profit motive that so many democratic societies see as essential to their way of life. 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, to be determined, purpose.

As with UNCLOS, many countries have specifically NOT acceded to its International Seabed Authority so as to continue their efforts to mine the seabed.[33]

CIL is, therefore, the policy of why countries do not accede to treaties and customary norms as much as it is due to the treaties they do ratify and the norms they do accept. The designation of the Moon and other celestial bodies to be the common heritage of mankind does not, in any way, preclude their exploration or their exploitation. Recalling the non-appropriation principle of the OST, 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. In addition, the failed (ratified by only 15 nations)

Moon Treaty was not signed nor ratified by any space-faring nation except India. This lack of acceptance is equally binding as to its designed failure.

The "why not" of signing, or ratifying, the Moon Treaty when the Outer Space Treaty 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 "common heritage of mankind" language is also seen in the OST. The Moon treaty, however, takes it 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. Governments, corporations, and individuals do not wish to be precluded from profiting from space mining! Once again, the Policy of the United States is to support commercial development.

7.3.1.3 The Legal Appropriation of Space Mineral Resources

Recall the non-appropriation principle of Article II of the OST. While scholarly commentary may seem confused at times, the *CJS* is clear that resources may be retrieved from space and celestial bodies. 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.

The first step to fully realize the strength of the CJS and humanity's future in the solar system is to properly apply the rules of interpretation to the *CJS*. The removal of resources is not sufficient to destroy the identity of the Moon or a celestial body in outer space. Removing a few rocks from a mountain will not change its character and identity, so too will the removal of resources from a celestial body likely not change the character of the solar system. Thus, utilizing resources from space will be permissible as it does not appropriate the celestial body from which they are gained for any nation's territory.

However, assume that the above does not hold. What recourse will then be had to the miner looking to harvest the mineral bounty of space? As explained, treaties and CIL can both be dynamic in light of subsequent agreements and practices. Even if the *CJS* once prohibited the removal and appropriation of any resources in space, it no longer does so. First, nations have recognized that moon rocks may be privately owned. How might this be unless the non-appropriation principle does not apply to such a resource? Article I of the OST states that "[o]uter space, including the moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies." It seems that "use" implies commercial exploitation of natural resources, as most scholars agree.

These arguments lead to the conclusion that SMR will be robust in the future as the financial, engineering and needs line up for growth beyond low Earth orbit.

8. PRELIMINARY FINDINGS, & RECOMMENDATIONS

The Academy study on space mineral resources (SMR) has made some preliminary findings and gathered recommendations that should enable companies to move forward and governments to support commercial enterprises.

Overall Recommendation: Study Group 3.17 has completed Phase One of the requested research and should have a final document available for publication during the last quarter of 2014. It has also identified many activities that should follow on the publishing of its current study report. As such, the study group should be "re-energized" as new emphasis should be placed on-going space mineral resource research. The Study group should be emphasizing the next level of analyses identifying critical steps in the evolution towards successful enterprises. This next level of research should focus upon major topics, such as:

- **1.Technological risk reduction and engineering designs**
- **2. Legal Regime**
- **3. Psychological and Social**
- **4. Economic Approach,** to identify a reasonable initial program for the near term
- **5. Asteroid Parallel** is attractive as the protection of the planet is also high priority

The following findings are broken up by category and recommendations are subsets of those

Finding 1 – Technological risk reduction and engineering design: The Mining of asteroids and of 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: Study Group 3-17 should establish a study team specifically to understand the design reference missions and necessary engineering steps to achieve mining of space resources. This working group should be established of 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 of commercial space mining firms may be different than the interests of academic scientific experts. This study should initiate an analysis between the SMR study group and the new Permanent Study Group on Space Elevators within Commission III. The goal would be to understand future in-space, to-space, and from-space infrastructures that would most complement the needs of humanity as it relates to opening up the Space Option for improvements on-planet.

Recommendation 1.2: Multiple year-long comprehensive international trade studies, initiated inside Study 3-17, and coordinated with the heads of national space agencies, 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. This trade study should be led by Commission III with the current space mineral resource companies and evaluate and conduct "people in the delay loop" simulations of the light speed control lag time. This particular skill set has been identified as a major challenge to space mining. In order to map the costs and benefits trades on a continuum of moving the processing facility to the ore body ("traditional mining methods") verses moving the ore body to the processing facility ("asteroid capture and return.") Commission III should lead this study with terrestrial and/or ocean mining companies.

Recommendation 1.3: The National University of Ireland should establish and chair a trade study of interested stakeholders to evaluate ways and means of dealing with the challenge of the long term radiation environment of space mining, which the draft study has identified is a major technical challenge to large scale space mining operations. The results would be incorporated into the 3-17 study report.

Recommendation 1.4: SMR physics are different than terrestrial mining and manufacturing physics. By developing both fields, a series of linked benefits can be created that will cascade across multiple fields of study. A research program [initiated inside the study group] identifying similarities and differences should be undertaken immediately by space agencies with the goal of finding novel approaches and stimulating the development of new technologies that will advance both terrestrial and outer space technologies. Asteroid impact mitigation techniques, new propulsion methods, and alternative energy re-utilization strategies are all areas that will immediately and directly benefits from this.

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 3-17, 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 so that all nations may prosper by the fruits of space. An example would be the development of regulations to be issued by the Federal Aviation Administration, Office of Commercial Space, in Washington DC.

Recommendation 2.2: Study Group 3.17 should continue to work with as many national space agencies as possible to build consensus and strengthen the international understanding and development of the specific justifications regarding the legality of exploiting SMR. An inter-agency protocol would be a useful tool to coordinate and develop this consensus and understanding.

Finding 3 – Psychological and Social: The psychological and social effects "in space" and "on the Earth" of developing space mineral resources on a large scale are unknown.

Recommendation 3.1: The Academy should establish a study group within 3-17 that deals with future long duration habitats, both in free-fall and on an asteroid or Lunar base. 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 feels 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 along with the profit motive of commercial success.

Finding 4 – Economic Approach: The economic effects "in space" and "on the Earth" of developing space mineral resources on a large scale are unknown. More analysis 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 Earth. For example, it needs to be pointed out that all of the money will be spent on earth creating jobs & infrastructure - this will bring vitality to the global aerospace sector.

Recommendation 4.1: Economic trade studies should be created by Study Group 3.17 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.

Recommendation 4.2: Asteroid retrieval costs are highly dependent upon orbital transfer energy composition and orbital timing (synodic period). These elements should be studied in detail by Study Group 3.17 so that these cost are properly reflected in the standardized SMR economic model.

Finding 5 – Asteroid Parallel: The asteroid impact hazard is a compelling international problem, one which begs for an international solution. Due to a combination of the richness of asteroid resources, and the strong set of crossover exploration/mitigation data needs (composition, mechanical strength, spin rates, etc.) as well as mining/mitigation technologies (drilling, anchoring, manipulation, etc.), a number of public-private partnership scenarios may exist that benefit both parties and offer cost savings.

Recommendation 5.1: Commission III's study group 3.17 should work with Space agencies, and examine and map the public-private partnership (PPP) crossover trade space. Options that maximize the value of PPP should be identified and promoted, including a trade study of how to create natural incentives or rewards for PPPs using policy & law that minimize public costs and maximize value to private parties.

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[16] [7.1] 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).

[17] [7.1] Peter Malanczuk, *Space Law as a Branch of International Law*, 1994 NETH. Y.B. INT'L L. 143, 147 (1995).

[18] [7.2] Major Robert A. Ramey, *Armed Conflict on the Final Frontier: the Law of War in Space*, 48 A.F. L. REV. 1, 74-100 (2000); 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.

[19] [7.2] The United States has not ratified the Vienna Convention, however, its courts have cited to it as CIL. Thus, it is at least partially binding 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).

[20] [7.2] 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; *Compare* Restatement (Third) of Foreign Relations Law § 301(1) (1987).

[21] [7.2] *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*, 34 VA. J. INT'L L. 405 (1994).

[22] [7.2] Vienna Convention, *supra* note 8, 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).

[23] [7.2] Ramey, *supra* note 6**Error! Bookmark not defined.**, 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..

[24] [7.2] Vienna Convention, *supra* note 8, at art. 31(3).

[25] [7.2] *See The S.S. Lotus*, (1927) P.C.I.J., Ser. A. No. 10, at 4, 18 ("Restrictions upon the independence of States cannot therefore be presumed).

[26] [7.3] *See* Ramey, *supra* note 6, at 66-67 ("Yet, what little customary law for space there is has been derived from the activity of very few States.").

[27] [7.3] 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

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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).

[28] [7.3] 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.

[29] [7.3] *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 31.

[30] [7.3] Paust, *supra* note 15 at 61.

[31] [7.3] *See* Paust, *supra* note 15 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.

[32] [7.3] *Customary Human Rights*, *supra* note 15, 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).

[33] [7.3.1.2] *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".