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Profitably Exploiting Near-Earth Object Resources

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Dreamers, science fiction writers, and even space scientists have speculated for decades about the potential benefits of asteroid mining, but for various technical, financial and political reasons, few practical steps have been taken towards making asteroid resource utilization a reality. Meanwhile, Earth-based observations and meteorite studies as well as recent robotic space-science missions have demonstrated that near-Earth objects (NEOs) do indeed possess vast stores of valuable resources and have suggested that these resources may, in some cases, be more accessible than lunar resources. Some NEO resources, such as platinum-group metals, are extremely valuable and increasingly in short supply here on Earth, while others, such as volatiles like water, hydrogen, and oxygen, can provide fuel and consumables for use in orbit and beyond to revolutionize space transport and to help open the solar system to development. Today, new commercial, scientific, and technical developments are coming together to make asteroid mining more feasible and financially attractive. This paper discusses NEO resources and their potential markets, NEO mining techniques, and the concrete financial and technical requirements for building and operating an economically viable NEO mining capability.

1. Introduction

We are approaching an important crossroads in history as we begin to experience the concrete global implications of limited supplies of many of the key natural resources upon which our industrial civilization is built. While we will not fully exhaust supplies of fossil fuels and other critical resources for decades or even centuries, we have reached a point where we can identify indisputable limits and begin to more fully appreciate their potential consequences. Fortunately, we have time to learn to better conserve existing natural resources and seek new supplies. Faced with these emerging realities, space resources – especially the resources of near-Earth space – become increasingly viable and even attractive options.[1]

Though limited, the resource base of our planet is complex and differentiated. As we have increasingly exploited its resources, we have aggressively explored the Earth in search of the most accessible deposits of ores and fuels. As we have used up the most accessible resources, we have had to dig deeper, accepting lower grade materials that are more costly to produce both in terms of financial investment and damage to our environment.

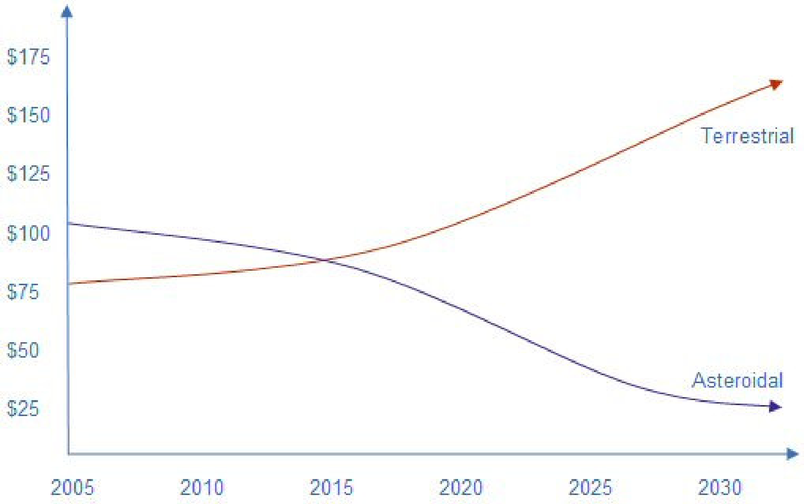
Independent of local resource scarcities and variations on individual planets, our solar system is differentiated on a large scale. Just as processes of crustal evolution have produced concentrations of useful materials at different depths and locations on the

Earth's surface, general processes of solar system evolution have produced concentrations of different resources in different parts of the solar system. These processes have produced vast supplies of a variety of materials distributed in zones, ranging from metal-rich silicates near the Sun through concentrations of organic and rocky material in the mid-solar system to concentrations of ices in the outer solar system. Melting has also concentrated metals in asteroidal cores exposed later by collisions and fragmentation.

Of particular interest for resource development are those asteroids and comets with orbits that make them relatively accessible from the Earth. Gravitational perturbations have caused samples of a wide variety of differentiated materials from various parts of the solar system to pass through the inner solar system where they can be more readily accessed and used by humans. These materials are likely to be the first non-terrestrial resources to be exploited for use both on Earth and in space and are likely to play an important role in supporting further space exploration.[2] This feedback loop will foster more human activity in space: early materials are likely to support space-based operations that will, in turn, be able to more cost-effectively acquire and process additional materials.[3] In addition, the negligible surface gravity of these objects will enable novel approaches to resource mining and processing and will make it easier to transport materials back to Earth/Earth orbit than to launch the same materials into space from deep within the "gravity wells" of the Earth, other planets, or their moons.[4]

In the future, the rising cost of resource acquisition on Earth will surpass the falling cost of acquiring equivalent or substitute materials in space. This is likely to provide the economic catalyst for large-scale acquisition and utilization of space resources. In fact, as we will show in this paper, for some resources, these costs may already be relatively close (Figure 1), and given favorable technical developments and target asteroid conditions, we may soon be able to obtain some resources in space at lower costs than we can mine and process them on Earth.

Figure 1. Relative Cost to Produce Ounce of Platinum, 2005-2030



Due to our incomplete knowledge of asteroid geology and conditions and the lack of tested technology solutions, initial recovery of non-terrestrial resources will be risky and expensive; however, the potential returns – including the ability to establish a viable planetary defense against asteroid and comet collisions – are enormous. The NEO Miner mission concept reviewed in this paper envisages use of multiple lightweight, teleoperated, and semiautonomous landers extracting and processing platinum group metals from highly-accessible near-Earth asteroids and returning these materials to Earth for sale.

2. Near-Earth Objects

Near-Earth objects (NEOs) are asteroids and short-period comets with orbits that regularly bring them close to the Earth and which may, in some cases, be capable of striking the Earth. More precisely, NEOs are asteroids and active or extinct comets having perihelion distances $q \leq 1.3$ Astronomical Units (AU) and aphelion distance $Q \geq 0.983$ AU. The tern is also sometimes used more loosely to include all comets (not just short-period ones) that cross the Earth's orbit. Those NEOs with orbits that actually intersect the Earth's orbit are called Earth-crossing objects.

Distinguishing between asteroids and comets is not always easy. The only hard and fast distinction is that comets have been observed to outgas. The outgassing indicates active sublimating volatiles, and several asteroids have been reclassified as comets after astronomers have observed outgassing. Asteroids either lack free volatiles or never get warm enough to outgas. While objects that appear asteroidal dominate the NEO population,[5] some scientists believe that as many as half the 3,100 near-Earth "asteroids" identified to date are actually dormant or extinct comets.[6]

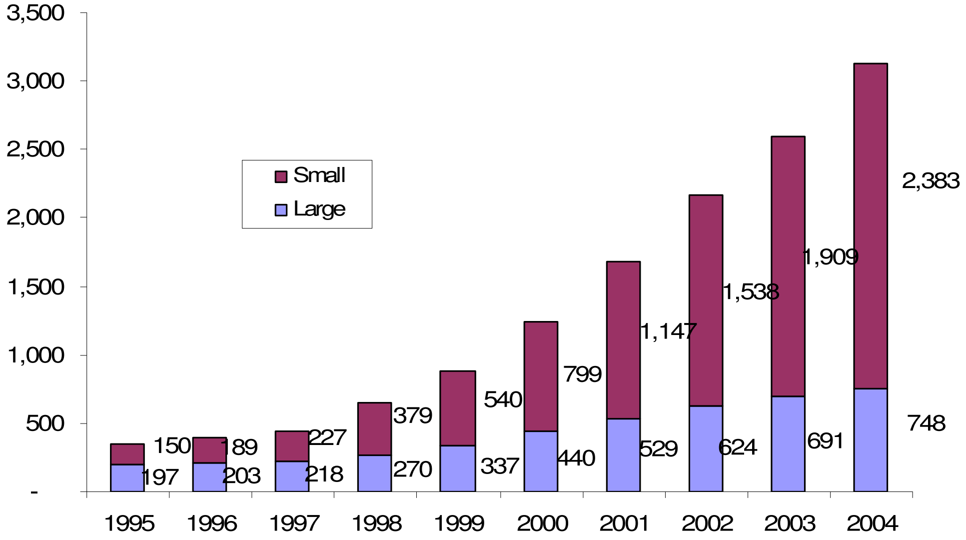
2.1. NEO Population

Current estimates suggest that NEO impacts capable of producing global ecological catastrophe occur roughly twice per million years.[7] As awareness of this threat has grown, considerable time and money has been invested in international efforts to build a comprehensive catalog of NEOs and their orbits:

- Spacewatch
- Near-Earth Asteroid Tracking (NEAT)
- Lincoln Laboratory's Near-Earth Asteroid Research (LINEAR)
- Lowell Near-Earth Object Survey (LONEOS)
- Catalina Sky Survey (CSS)
- Bisei Spaceguard, Japan

These efforts have contributed to a dramatic increase in the number of objects identified over the past decade. By the end of 2004, researchers had catalogued more than 3,100 NEOs, including 748 larger than 1 kilometer in diameter (Figure 2).

Figure 2. Known Near-Earth Objects, 1995-2004 (Number known by Year)



Note: In this context, "large" is defined as NEOs with absolute magnitudes (H) of 18.0 or brighter. This roughly corresponds to 1-kilometer diameter and larger NEOs.
Source: Data compiled by Alan Chamberlin. (NASA/JPL); http://neo.jpl.nasa.gov/stats/

Astronomers estimate that there are still many NEOs yet to be discovered, especially ones less than 1 kilometer in diameter. The total NEO population over 1-kilometer in diameter is estimated to be between 1,000 and 1,200.[8]

2.2. Shape and Rotation

During the past decade, Earth-based radar studies have dramatically improved our knowledge of NEO shapes, surface properties, and rotation. These results indicate that NEOs come in all shapes and sizes, from featureless spherical balls to irregularly shaped objects with craggy, bumpy, and cratered surfaces. These studies have also shown that NEOs exhibit complex rotational states (including fast rotators having periods between 2 and 20 minutes and asteroids exhibiting rotation around a non-principal axis), and a few are binary or have satellites.[9] To date, radar studies have been conducted on more than 100 NEOs.[10] Continuing radar studies will be an essential step in "prospecting" target asteroids for mining, with the results of the studies providing rich data sets for use in determining desirable targets and creating detailed computer simulations of potential missions.

2.3. Size

The size distribution of asteroids – both Main Belt and Near Earth – can be described as the result of a cascade produced by successive impacts and fragmentations. The results extend over 12 orders of magnitude – from over 1,000 kilometers in diameter to micrometer dust.[11] Generally, the number of objects increases dramatically as the size decreases, and there arc many more small objects than large ones. Typically, as the size decreases by a factor of 10, the number of objects increases by a factor of approximately

100. So, the current catalog of identified near-Earth objects includes many relatively small asteroids (mostly with diameters from 0.5 to 10 kilometers) of mixed compositions. As we will discuss later, size is an important consideration in determining which NEOs are the best candidates for mining operations.

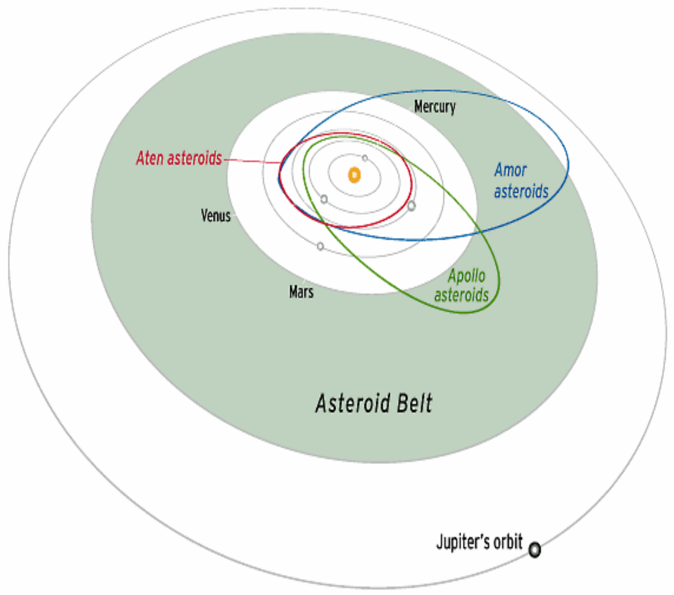
2.4. Orbits and Accessibility

The asteroid belt and the suites of comets and asteroids in the outer solar system are reservoirs from which our samples of near-Earth bodies are drawn, partly at random. Most are probably fragments of main-belt asteroids, but a substantial fraction may be burned-out comets that originated in the outer solar system, namely in the Kuiper Belt and the Oort Cloud. The latter include carbonaceous stony objects with various quantities of trapped volatiles.

The sequences of perturbation processes can put both asteroids and burned-out comets onto Earth-crossing orbits. For example, Jupiter resonances throw objects out of the mid-belt. Mars gravitational perturbations throw objects out of the extreme inner edge of the belt. Meanwhile, giant planet perturbations send outer solar system debris into the inner solar system. As a result of these various forces, the objects that cross Earth's orbit are a heterogeneous mixture of different types from different source regions.[12]

Near-Earth asteroids are classified by orbital parameters into Apollos, Amors, and Atens (Figure 3). In addition, Arjunas are a group of small objects in very Earth-like, and therefore very accessible orbits.

Figure 3. Near-Earth Object Orbits



Accessibility is defined in terms of change-in-velocity requirements (Δ-v) for outbound and return trajectories. In space, the parameter that determines how easy or difficult it is to deliver mass from one orbit to another is not distance but the required velocity change

(Δ-v) needed to perform the transfer. One characteristic that makes NEOs particularly attractive for resource utilization is the relatively low Δ-v required to reach them and return resources from them. Many near-Earth asteroids require less energy to reach than the surface of the Moon, and return to Earth orbit requires far less Δ-v than return from the Moon (Figure 4).

Figure 4. Mission Energy Requirements (Δ-v)

Transfer	**Delta-V** (km/s)
Earth surface to low-Earth orbit (LEO)	8.5
Earth surface to escape velocity	11.2
Earth surface to geosynchronous orbit (GEO)	11.8
LEO to escape velocity	3.2
LEO to Mars transfer orbit	3.7
LEO to GEO	3.5
LEO to highly-elliptical Earth orbit (HEEO)	2.5
LEO to Moon landing	6.3
LEO to near-Earth asteroid[a]	4.0
Lunar surface to LEO (aerobraking)	2.4
Near-Earth object (NEO) to Earth transfer orbit	1.0
Phobos/Deimos to LEO	8.0

Δ-v is a scalar measure for the amount of "effort" needed to carry out an orbital maneuver, i.e., to change from one orbit to another. A Δ-v is typically provided by the thrust of a rocket engine. The time-rate of Δ-v is the magnitude of the acceleration, i.e., the thrust per kilogram of total current mass, produced by the engines.

a. Typical near-Earth asteroid; actual Δ-v varies by individual asteroid.

In fact, the mission velocity Δ-v needed to reach selected near-earth, low-Δ-v target objects is not much greater than that needed to place a communications satellite in geosynchronous orbit (GEO). The Δ-v required to place material from these targets on an Earth-orbit-intercept trajectory may, in selected cases, be far less than that required to lift mass into orbit from the surface of the Earth, and can be imparted gradually, over several weeks, substantially reducing demands on the propulsion system.

Lewis has estimated that 10 percent of all NEOs are more accessible in terms of Δ-v than the Moon and are much easier to return to Earth from than the Moon.[13] Maybe fifty percent of these are likely to have desirable resources that can be readily extracted. Using the Shoemaker-Helin formulae[14] for estimating the probable likely minimum Δ-v for Hohmann transfers to and from these bodies, Sonter calculated that about 6 percent of the near-Earth asteroids known in 2001 are more accessible than the Moon, having a minimum outbound Δ-v from LEO for rendezvous of less than 6 km/s. He estimated that about twice this percentage have "global minimum" outbound Δ-vs from LEO under about 6.5 km/s. A few have outbound Δ-vs under 4.5 km/s, with at least one known object (1991 VG) having an outbound Δ-v slightly under 4.0 km/s. Similarly, a few have Δ-vs for return departure on the order of 1 km/s.[15] Analysis by Sonter and others suggests that the lowest Δ-v targets for initial resource development are the low eccentricity, low inclination subset of the "Earth-Approaching" Apollo, Amor, or Aten asteroids or any as-yet undiscovered Earth-Trojan asteroids.[16]

Another major Δ-v requirement for a mission requiring return of product from an asteroid is for Earth-capture from heliocentric orbit into highly elliptical Earth orbit (HEEO), and then subsequently its reduction into LEO. Capture via powered or unpowered lunar flyby, followed by aero-braking or potentially by direct aero-breaking or aero-entry are the most energy-efficient solutions to meeting the Δ-v requirements for return of asteroid resources to Earth.

Careful target selection will be critical to any commercial NEO mission because the lower the return propulsion requirement, the lower the mass that has to be transported to the asteroid or mined to produce propellant and therefore the lower the mining equipment and the power supply mass, and the larger the proportion of recovered mass that can ultimately be sold for revenue. In addition, the fact that many NEOs remain well within the inner solar system during their orbits simplifies spacecraft thermal-design and power-generation considerations.[17] Thus, orbital characteristics of individual target asteroids drive energy requirements and mining seasons. Highly detailed models of potential mission scenarios can be created based on this data and used to identify likely targets. As additional asteroids are discovered, an even larger range of potential missions can be modeled.[18]

2.5. Composition

The geological characteristics of NEOs are governed by the environment in which they formed. Most asteroids condensed just after the formation of the solar system, as reflected by their age (approximately 4.7-billion years). The environment allowed larger bodies, especially planets, to differentiate gravitationally – pulling such elements as iron, nickel, and platinum group metals (PGMs) to the core. There is a strong correlation to the thermal environment as well. Bodies forming at the edge of the solar system cooled more rapidly, slowing or stopping this differentiation process. Smaller bodies did not develop sufficient mass for gravity separation and reflect the original distribution of elements from the supernova event. PGMs are quite abundant in these small bodies, called chondrites after their agglomeritic nature, hinting at the original distribution of elements in the solar nebulae. As noted above, this solar-system-wide differentiation mirrors the localized differentiation on Earth, especially the sequestering of heavy elements in the planetary core.

Based on spectroscopic studies and on “ground truth” from meteorite studies, near-Earth asteroids appear to possess extremely variable and wide-ranging compositions.[19] They include stony silicates with enhanced levels of semiconductors and of platinum group metals;[20] bituminous or carbonaceous bodies;[21] dormant or extinct comets with remnant ices and clay minerals; and reduced metallic bodies, composed in large part of nickel-iron alloy.[22] All of these substances may someday be valuable feedstock in the construction of infrastructure and supply of fuel for development of an orbital economy.

The compositions of asteroids are inferred from laboratory studies of meteorites and from spectral reflectivity studies of asteroids at ultraviolet, visible, and near-infrared wavelengths. Meteorite samples are the primary source of detailed data for asteroid chemical composition, especially trace metals. A rough spectral taxonomy of asteroid types separates them into three broad categories:

- C-type (carbonaceous) asteroids are water-bearing with very high contents of opaque, carbonaceous material.
- S-type (stony) asteroids are anhydrous and rocky, consisting of silicates, sulphides, and metals.
- M-type (metallic) asteroids exhibit high radar reflectivity characteristic of metals.

About half of the kilometer-sized NEO population is believed to be carbonaceous, and thus carbon- and water-rich.[23] If one assumes the other half to be dominated by S-type asteroids with a few percent of M-type bodies, one can estimate that the non-carbonaceous asteroids contain the following: about 20 percent metallic iron-nickel alloy; about 6 percent of the ferrous sulphide mineral troilite, and large amounts of olivine, pyroxene, and plagioclase feldspar; trace amounts of rare and valuable metals (especially PGMs) and non-metals (e.g., arsenic, selenium, germanium, phosphorous, carbon, sulphur). The mineralogical, chemical and physical properties of four different asteroid types based on meteorite samples are shown in Figure 5.

Figure 5. Mineralogical, Chemical and Physical Properties of Asteroids

	Mineral	C2-Type	C1-Type	S-Type	M-Type	Lunar Regolith
Free Metals	Fe	10.7%	0.1%	6-19%	88%	0.1%
	Ni	1.4%	—	1-2%	10%	—
	Co	0.11%	—	0.1%	0.5%	—
Volatiles	C	1.4%	1.9-3.0%	3%	—	0.014%
	H2O	5.7%	12%	0.15%	—	0.045%6
	S	1.3%	2%	1.5%	—	0.12%
Mineral Oxides	FeO	15.4%	22%	10%	—	15.8%
	SiO2	33.8%	28%	38%	—	42.5%
	MgO	23.8%	20%	24%	—	8.2%
	Al2O3	2.4%	2.1%	2.1%	—	13.8%
	Na2O	0.55%	0.3%	0.9%	—	0.44%
	K2O	0.04%	0.04%	0.1%	—	0.15%
	P2O5	0.28%	0.23%	0.28%	—	0.12%
	CaO	—	—	—	—	12.1%
	TiO2	—	—	—	—	7.7%
Physical	Density (g/cm^3)	3.3	2.0-2.8	3.5-3.8	7.0-7.8	1.5-1.9

This table depicts four representative asteroids based on four different meteorite types. Note that individual meteorites vary dramatically in composition, and this table presents samples from within only four categories.

Source: B. O'Leary at al., Retrieval of Asteroidal Materials, Space Resources and Settlements, NASA SP-428 (1979) pp. 142–155; Apollo 11 lunar soil sample data.

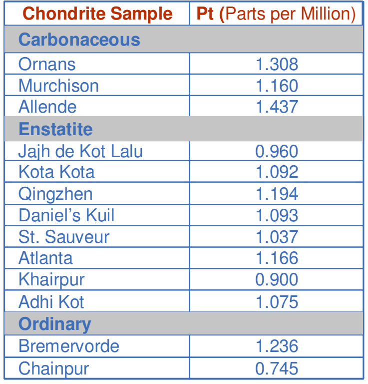
Carbonaceous asteroids contain important commodities for life support and are therefore important targets for future mining. Our knowledge of these bodies is based on the chemical analysis of meteorites believed to come from these parent bodies, known as carbonaceous chondrites. Carbonaceous chondrites are named after the tiny pellets of rock called chondrules embedded in them, a result of a kind of chemical fractionation unique to small bodies. They are crumbly, and probably came from parent bodies that were too small to undergo a large degree of gravitational differentiation or are collision ejecta from less than catastrophic collisions of slightly differentiated bodies.

2.6. Platinum Group Metals

Platinum-group metals (PGMs) include the six metallic elements platinum, palladium, rhodium, ruthenium, iridium, and osmium. Platinum occurs either in placer deposits or in host mineral deposits. Other PGMs are often alloyed with platinum, and gold is a common deposit on platinum crystals. While PGMs may have been abundant during stellar formation, they are highly depleted in the Earth's crust and are found in only a few locations on its surface. Many asteroids are believed to be made up of primitive core materials rich in sidereal elements such as rgw PGMs that are so rare in the Earth's crust. PGMs are found dissolved among metallic phase grains, especially in ordinary chondrites.

PGMs represent perhaps the most attractive NEO resources. Unlike other potential NEO resources, PGMs have commercial values of thousands of dollars per kilogram, making them especially attractive as candidates for refining and returning to Earth. In fact, Lewis and Meinel have asserted that "all common classes of meteorites contain higher concentration of platinum-group metals than the richest ore bodies in Earth's crust,"[24] and a growing body of evidence supports this conclusion that concentrations of platinum and other PGMs are significantly higher in many asteroids than concentrations found in the best mines on Earth. On Earth, we observe concentrations of 4 to 6 parts per billion (ppb) in the best mines because there is little platinum in the Earth's crust (due to the processes discussed above). Concentrations of 30 to 60 ppb are hypothesized in many asteroids with a potential of 250 ppb or even 1,000+ ppb based on meteorite studies (Figure 6).[25]

Figure 6. Platinum Concentration in Selected Chondrite Meteorite Samples



Chondrite Sample	Pt (Parts per Million)
Carbonaceous	
Ornans	1.308
Murchison	1.160
Allende	1.437
Enstatite	
Jajh de Kot Lalu	0.960
Kota Kota	1.092
Qingzhen	1.194
Daniel's Kuil	1.093
St. Sauveur	1.037
Atlanta	1.166
Khairpur	0.900
Adhi Kot	1.075
Ordinary	
Bremervorde	1.236
Chainpur	0.745

Note: Analytical uncertainties are approximately +0.2% for Pt.
Source: M.F. Horan, R.J. Walker, and J.W. Morgan, "High Precision Measurements of Pt and Os in Chondrites," Lunar and Planetary Science XXX (2001).

Lewis and Hutson note that the metal fraction of the typical LL chondrite contains 50 to 60 **parts per million** (ppm) of platinum-group metals, and the concentration in the metal grains in CV and CO chondrites could reach 100 to 200 ppm![26] In addition, platinum-rich ore may actually be ponded in loose regolith on some asteroid surfaces, making mining relatively easy. One platinum-rich 1-kilometer asteroid may contain more platinum than has been mined in history plus that contained in all known terrestrial reserves.

The most important target selection consideration besides asteroidal composition is the ease of mining and extracting the metal. Mining operations will be easier on larger asteroids because they are likely to have many deep ponds of mineral-rich regolith. Mining metal from an M-type asteroidal core is likely to be extremely difficult compared to extracting it from the chondrite asteroidal regolith.

2.7. Volatiles

The other NEO resources of particular interest are the volatiles locked up in these bodies. Comets are thought to be covered by a layer, between 10 centimeters and 10 meters thick, of dirt and/or dark carbonaceous sooty material. A little less than half of the mass of the typical comet is believed to consist of rock-like dust bound together by the ices that make up the rest of the comet (approximately 50-percent water ice, 10-percent CO and CO2, and 0.5-percent of a conglomerate of carbon, hydrogen, oxygen and nitrogen (CHON) materials).[27]

The reason both active and dormant comets are attractive from a space resources development perspective is the presence of so many volatiles that could one day be tapped as sources for water, oxygen, and hydrogen fuel for space missions. These objects are rich in the raw materials required to make rocket propellant, construction materials, and even plant food. They are the crucial elements for operating in space and sustaining life there.

Volatiles are likely to be easier to extract and process in space than other types of resources (e.g., metals, semiconductors). There is no complicated chemistry or need to reduce rock to rubble. Conceptually, one might need only to vaporize the ice and condense it into a cold finger that can be transported to a desired location or even tapped directly to fuel a solar-thermal steam rocket.

The availability of inexpensive, locally produced propellants on orbit and beyond would revolutionize the economics of space operations. Many space-derived propellant systems have been proposed.[28] By far the greatest bulk of materials launched from Earth into space are volatile propellants. In space, expendables used on the International Space Station and manned space missions consist overwhelmingly of volatiles (e.g., air, water, propellant). In addition, the largest proportion by far of materials used by most processing industries is made up of volatiles and organics. Extraction and processing of volatiles from comets combined with technologies such as orbital fuel processing and storage depots[29] and even solar-thermal steam rockets[30] could enable a wide variety of new possibilities along the path from our current small-scale space operations to large-scale space industrialization. Native volatiles could be processed to supply space operations, while making possible new industries with low up-front investment. Bootstrapping of transportation with native fuels and industry with chemical microreactors could provide the technological and economic resources for large-scale space industry and space colonization.

2.8. Advantages of NEO Mining

While untested and fraught with engineering challenges, NEO mining has the potential to dramatically change the dynamics of many segments of the natural resources industry. It transforms the dynamics and economics of almost every aspect of resource production. Robotic mining of near-Earth objects has several potential advantages over traditional terrestrial mining (Figure 7).

Figure 7. Potential Advantages of NEO Mining

	Description
Prospecting	▪ High proportion of targets are likely to succeed as “ore bodies”
Processing	▪ High grade ore implies easier extractive metallurgy
Mineral Rights	▪ No existing landowners to negotiate with or expensive rights to acquire
Environment	▪ No environmental laws or constraints increasing mining or processing costs; removes environmentally destructive activities from terrestrial ecosystem
Waste Disposal	▪ Waste disposal during extraction and processing is not a concern
Lead Time	▪ Short lead-time to production because initial mission to target is designed to return product – trial mining is relatively easy
Capital Expenditures	▪ Fewer large capital expenditures (e.g., mine, plant, town, port, other infrastructure) and plant may actually be leased (eliminating most CAPEX)
Scalability	▪ Plant is can be so small and inexpensive that it is eventually mass produced and discarded after use (making model extremely scalable)
Flexibility	▪ Feasibility hurdles lowered due to ability to move to a new target if first target does not meet expectations
Reusability	▪ May be possible to relocate “plant” at end of “mine life”

Source: Adapted from M.J. Sonter, Near Earth Objects as Resources for Space Industrialization Solar System Development Journal 1(1) (2001), pp. 1–31.

Based on what we have learned about asteroid geology and operating in micro-gravity environments, we can conceive of radically new approaches to mining on an asteroid that may ultimately become much more cost-effective than more traditional mining operations. These advantages and all of the other attractive features of NEOs as targets for mining operations would appear to justify the risk and investment required to take the first steps.

3. Markets

The ability to cost-effectively meet existing market needs is the *sine qua non* of any successful space resources venture. This objective can be divided into three components. First, capital expenditures must be minimized as much as possible. Second, the time required to generate real revenues must be minimized. Third (and really a corollary of the second), real markets must currently exist for the planned products.[31] Many proposed space ventures are destined to fail because their advocates have not adequately addressed these basic economic considerations.

3.1. Need for Near-Term Markets

When exploring the potential commercial viability of various space resources opportunities, the ideal candidates are those where an actual market exists today for the product. Obviously, to make money a product and a market are required. Markets are based on need. There is no market if no one wants to buy the product. Would-be space entrepreneurs have identified many products over the years, but most of the markets are non-existent, hypothetical or government dependent. No independent commercial demand exists today for space habitats and astrocrete or orbital water, oxygen, and metals or helium-3 on Earth except to supply government-sponsored activities.

This requirement for existing markets is the reason space tourism is attracting so much attention in general discussions of commercial space development. Several market studies[32] suggest that there is a readily identifiable group of customers who are willing to spend a specific amount of money today for the opportunity to travel into space. Most space resources development schemes, such as proposals to mine lunar helium-3 and return it to Earth for use in fusion power plants,[33] are dependent not only on investment in the infrastructure to mine and return lunar helium-3 but also on the massive investment in time and capital required to actually build a working helium-3 fusion reactor (if that is possible at all in the foreseeable future).

Even smaller-scale activities, such as proposals to extract volatiles from comets or potential ice deposits at the lunar South Pole to produce oxygen, water, and fuel for use in space, require not only the investment in the mining and processing of the products but also in the development of a costly space-based infrastructure for actually utilizing those products. Decades of investment and detailed research have gone into studies of building blocks for a potential market on orbit for volatiles produced in space (e.g., orbital maneuvering vehicles,[34] orbital refluiding,[35] orbital fuel depots[36]) but no such infrastructure yet exists. Without that infrastructure in place, no viable market exists.

What makes platinum group metals (PGMs) an attractive product is the existence today of an easily identified, well understood market. Given a reasonable estimate of the cost to produce a quantity of platinum and deliver it to a given buyer at a given time in the future, one can calculate the financial return required to justify the investment with a reasonable degree of accuracy. The existence of the clearly defined market means that one can focus on the nuts and bolts of the capability required to address that market, rather than on building the market itself. And, ironically, this is in many ways an easier business case to build and defend than many of those for the Earth-based businesses that were so readily funded in the late 1990s.[37]

3.2. Target Markets

Based on the need to achieve relatively rapid return on a reasonable investment, an appropriate approach at this point is to focus on the return to Earth of platinum group metals and complimentary markets (Figure 8).

Figure 8. Overview of Target Markets

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

First and foremost, the growing industrial demand and demand for use in jewelry will create a large and sustainable market for platinum and other platinum group metals. Second, the ability to deliver a rich supply of new scientific data as well as a broad selection of actual asteroid surface samples at costs far below that required to mount dedicated science missions, make this capability attractive to academic and research institutions. Third, unique entertainment and sponsorship opportunities hold the promise of attracting customers and partners willing to participate in the production of media content and to purchase content and sponsorship opportunities. Longer term, new markets will develop for near-Earth object resources on orbit:

- Volatiles for refueling and supply of manned spacecraft
- Semiconductor elements for production of photovoltaic arrays on orbit
- Metals and other materials for orbital construction

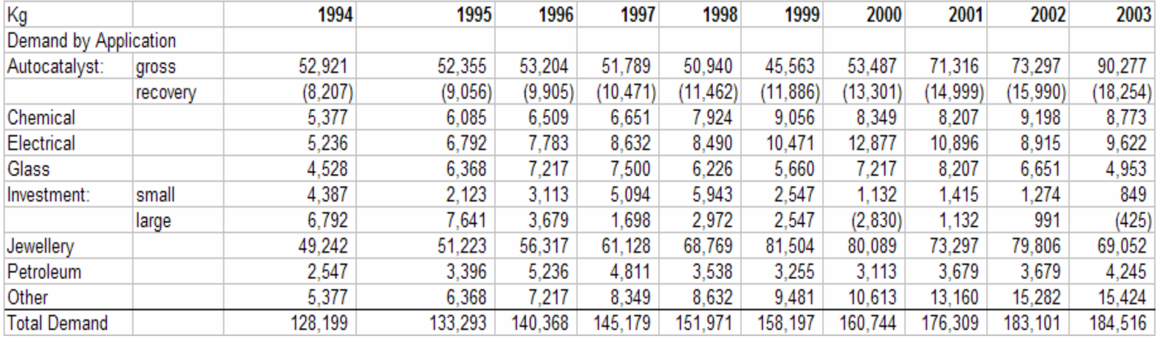
The capabilities required to address the platinum and scientific data markets have the potential to build a strong foundation for the longer-term orbital markets.

Initial analysis suggests that the successful launch and operation of the NEO Miner mission concept discussed later in this paper might be capable of producing between $400 million and $1 billion in revenues from a single 3-year asteroid mission, with most revenue derived from the sale of platinum, but with sales of scientific samples and data and sponsorships and media licensing agreements sufficient to offset most of the development and launch costs.

3.3. Platinum Group Metals Markets

Demand for platinum and other PGMs will continue to be very strong, and under some scenarios, demand may even outstrip known terrestrial reserves. The global platinum market was worth about $5.5 billion in 2003 with the two largest components by far being automotive ($2.7 billion) and jewelry ($2 billion). The volume demand for platinum by industry segment is shown in Figure 8.

Figure 9. Platinum Demand by Application, 1994-2003 (In Kilograms)



Kg		1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Demand by Application											
Autocatalyst:	gross	52,921	52,355	53,204	51,789	50,940	45,563	53,487	71,316	73,297	90,277
	recovery	(8,207)	(9,056)	(9,905)	(10,471)	(11,462)	(11,886)	(13,301)	(14,999)	(15,990)	(18,254)
Chemical		5,377	6,085	6,509	6,651	7,924	9,056	8,349	8,207	9,198	8,773
Electrical		5,236	6,792	7,783	8,632	8,490	10,471	12,877	10,896	8,915	9,622
Glass		4,528	6,368	7,217	7,500	6,226	5,660	7,217	8,207	6,651	4,953
Investment:	small	4,387	2,123	3,113	5,094	5,943	2,547	1,132	1,415	1,274	849
	large	6,792	7,641	3,679	1,698	2,972	2,547	(2,830)	1,132	991	(425)
Jewellery		49,242	51,223	56,317	61,128	68,769	81,504	80,089	73,297	79,806	69,052
Petroleum		2,547	3,396	5,236	4,811	3,538	3,255	3,113	3,679	3,679	4,245
Other		5,377	6,368	7,217	8,349	8,632	9,481	10,613	13,160	15,282	15,424
Total Demand		128,199	133,293	140,368	145,179	151,971	158,197	160,744	176,309	183,101	184,516

Source: Johnson Matthey 2004.

The growing number of automobiles and the potential large-scale adoption of fuel cell technology are likely to drive significant growth in demand for platinum and other platinum group metals over the next twenty years. The platinum jewelry market continues to grow rapidly as well, fueled significantly by growing demand in Asia.[38] In addition to supplementing the traditional platinum supply, opportunities may exist to exploit the unique quality of ultra-pure asteroid-derived platinum to market jewelry and other precious objects made from it at premium prices.

According to a British government study,[39] even without full-scale fuel cell adoption, the transportation industry uses a significant portion of the world's PGM output. As of 2002, the automotive industry used about 71 metric tons of platinum and palladium annually, equal to 20 percent of global production. This is expected to increase with more stringent pollution controls on diesel automobile engines in Europe and North America.

The petroleum industry uses platinum in the catalytic cracking (breaking down of heavy hydrocarbons into lighter ones) of hydrocarbons in refineries. The electronics industry is using increasing amounts of platinum and palladium in the manufacture of hard disk drives and capacitors. In the electronics-related glass industry, demand for platinum is accelerating because it is a required in the production of liquid crystal displays. The chemical industry uses platinum as a catalyst to lower the energy required for a wide range of chemical reactions, such as those used to produce silicone. The "other" category above includes applications such as platinum fillings, spark plugs, pacemakers, catheters, and many other items that require a high-temperature-resistant or a corrosion-resistant metal.

Platinum prices have remained close to historic highs over the past two years and are expected to remain strong. Current high platinum prices (e.g., $872/oz on May 2, 2005) highlight the critical impact that a supply/demand imbalance can have on price.[40]

Increasing demand from Chinese jewelry market has been driven by China's economic expansion since the mid 1990s. Increasing demand from transportation is due to more stringent emissions controls on diesel vehicles combined with growing market penetration of diesel vehicles in Europe, and anticipated higher auto demand due to economic recovery as well as to fuel cell adoption in the longer term. In addition, mutual funds have increased their investment in platinum.[41]

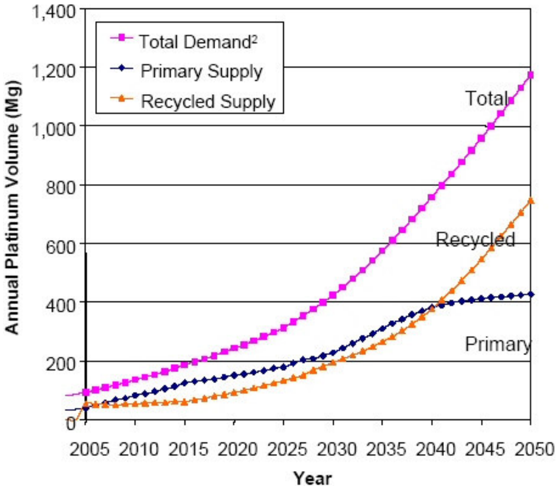
As the same time as demand remains strong and growing, mine expansion efforts are not meeting published company goals. The strong rand has inhibited new capital investment in South Africa. Meanwhile, an oversupply of palladium and other PGM byproducts has reduced margins. [42]

Fuel cell adoption may ultimately become the most important dynamic in the platinum market. Platinum is critical to fuel cell performance because it is critical to achieving the required levels of fuel cell power density and efficiency. It is essential to the catalysis of anodic and cathodic reactions in the stack. It is important to the catalysis of reforming, shift, and preferential oxidation reactions in the fuel processor.

The fuel cell industry's demand for platinum and other PGMs is expected to eventually dwarf all other sectors and will place an incredible strain on the supply of platinum and the environment. Just as O'Neill[43] justified investment in the development of his massive L5 space colonies with the need to construct space solar power satellites (SSPS) to meet the world's growing energy needs, exploitation of asteroid resources in part be justified by the desire to find new, more environmentally friendly ways to meet our energy needs in the face of fossil fuel depletion.

One step that can be taken to address growing fossil fuel demand is to shift from a petroleum economy to a hydrogen economy, where the gasoline internal combustion is replaced by hydrogen fuel cells. However, one potentially serious roadblock to this shift is the requirement for platinum as a catalyst in fuel cells,[44] with limited platinum reserves and high platinum production costs may slow or even halt fuel cell adoption (Figure 10).

Figure 10. Potential Impact of Fuel Cell Adoption on Platinum Supply and Demand



Note: Total demand includes transportation, jewellery, industrial applications, and stationary fuel cell power generation.
Source: U.S. Department of Energy, "Platinum Availability and Economics for PEMFC Commercialization," DE-FC04-01AL67601 (December 2003).

Many studies suggest that widespread fuel-cell adoption could rapidly deplete global platinum reserves. For example, a September 2003 study[45] on potential platinum requirements for hydrogen fuel cells produced for the UK Department of Transport supports the case that we may not have enough platinum to enable a shift to a hydrogen economy. A more recent US Department of Energy study[46] suggests that in some scenarios a shift to a hydrogen economy might put severe strains on global platinum reserves. However, the DOE study suggests that platinum depletion may not be as significant a problem under some slower fuel cell adoption scenarios.

Other studies have echoed these findings. A Swedish study found that "[i]n the baseline scenario, the demand for primary platinum in the 21st century amounts to 156 [billion grams], and current reserves and identified resources of platinum would be depleted in the 2050's and 2060's, respectively."[47] Meanwhile, Torn and Das found that under the worst case scenario, half of known PGM reserves will be exhausted before mid-century. This scenario is characterized by a high demand for new vehicles in the developing countries and high penetration of reformer-equipped fuel cell vehicles with relatively high amounts of PGMs.[48] Borgwardt calculated that unrestricted US fleet conversion to fuel cell vehicles would require 66 years and 10,800 tons of platinum. If US platinum consumption remains at its current level of 16% of annual world production, fleet conversion would require 146 years and 15,200 tons of platinum. "These results imply that, without alternative catalysts, fuel cells alone cannot adequately address the issue facing the current system of road transport."[49]

Based on the findings of these studies, analysts can differ on whether a full-scale shift to a hydrogen economy is possible given current terrestrial platinum reserves. What is confirmed by these studies, however, is that platinum is a scarce resource on Earth that will continue to be extremely valuable for the foreseeable future. This makes platinum an ideal candidate for space-based production and return to Earth for sale.

3.4. Scientific Data and Sample Return

Scientific payloads and sample returns are complimentary to primary mission and can be easily incorporated into mission design. Potential customers include academic and research institutes as well as government agencies. The initial design proposed here calls for a set of landers with the ability to collect extensive data both from orbit around the target asteroid and multiple surface locations, as well as to deliver multiple ejectable science payloads and return dozens of sample sets for multiple customers. Sales of scientific data sets includes the ability to purchase data sets or buy space on the vehicle for instruments and ejectable payloads. The design calls for the potential to deliver dozens of sample sets from the asteroid in combination with the data sets and other detailed contextual data.

The concept of selling scientific data sets and the ability to fly instruments and ejectable payloads to a target asteroid is not new. In the late 1990s, Space Development Corporation (SpaceDev), a San Diego-based space systems start-up, proposed a mission called Near Earth Asteroid Prospector (NEAP) for which it offered these services at a fixed price. SpaceDev's NEAP proposal reportedly had 6 or 7 potential customers signed up. SpaceDev's NEAP commercial price list line items ranged from a low of $10 million for an ejectable experiment, to $12 million for instruments integrated into the spacecraft, to a high of $15 million for science datasets returned by experiments financed and owned by SpaceDev. SpaceDev estimated that it had to fly five or six $10 million ejectable payloads, or five $12 million integrated payloads, or four datasets at $15 million each, or any combination that would produce total revenues of around $60 million. One factor helping to make this concept viable at the time was the ability for organizations wishing to buy sample sets or space on the craft to use NASA Opportunity mission funding. At the time, NASA's Dr. Carl Pilcher confirmed that SpaceDev's NEAP could be considered a Mission of Opportunity by those organizations, enabling them to access government funding to participate in the NEAP mission.[50]

Sample masses returned must be sufficient to determine the major physical properties of the samples like density, porosity, and mechanical strength. These properties must be determined in order to understand the geophysical properties and internal structures of asteroids. A considerable amount of research was conducted in the 1960s and 1970s to determine the minimum mass required for an accurate determination of bulk compositions of chondrites, with an often-quoted mass being 10 grams.[51] If several laboratories are to independently make such determinations, then the required sample masses will be several tens of grams. An additional consideration is to assure that there is adequate mass to determine the major structural components in a statistically significant way. For example, what are the mineral and phase proportions and what are the chondrule and metal grain size distributions? For many years, these parameters have been considered crucial in understanding meteorites. Such considerations lead to the requirement that each sample must be approximately100 grams.[52]

Is the scientific data and sample market viable today? The SpaceDev experience suggests that it might be a realistic option to help offset the costs of an initial mission. Certainly, it is very complimentary of the primary mission, since much of the instrumentation required to deliver these services is necessary for the primary mission. Scientific data and sample returns from a single mission could generate significant incremental revenue. Based on the SpaceDev experience and the comparative costs for more traditional missions it would seem realistic to price sample returns at $7 to $10 million each for as many as ten sets, as well as $3 to $5 million for various data sets. Conservatively this could generate $50 to $100 million in incremental revenues, offsetting much of the cost of the development and launch of a mining mission.

3.5. Entertainment and Sponsorships

In the late 1990s, having observed many Internet ventures that seemed to be supported by little more than advertising and marketing arrangements, several space entrepreneurs set out to build space ventures supported only by advertising, licensing, and marketing.[53] Needless to say, none of these ventures made it even as far as the contemporary dot-coms that eventually collapsed under their own weight as well.

The lesson of this experience is not that there are no revenue streams to be derived from savvy marketing and licensing efforts, but that one should not attempt to build an entire space venture on this revenue model alone. The fact is that entertainment, advertising, licensing, and sponsorships represent a potentially lucrative means of offsetting a portion of initial mission costs. In addition, they provide a valuable marketing tool for the venture that can attract investors and other contributors.

Sponsorship is the financial or in-kind support of an activity, used primarily to reach specified business goals. Sponsorship should not be confused with advertising. Advertising is considered a quantitative medium, whereas sponsorship is considered a qualitative medium. It promotes a company in association with the sponsee. The sponsorship market, which reached $25 billion globally in 2001, could clearly be an important source of publicity and funding for emerging space markets. While the majority of the market (nearly 70 percent) is dedicated to sporting events, the educational and arts sponsorship markets collectively constitute nearly $3 billion in revenues.[54] Specific sponsorship opportunities consist of agreements by which brands may be associated with the mission and potentially include naming rights, various advertising placements and even the delivery of logos and objects to the target asteroid. Related to these sponsorship rights are advertising agreements, through which revenue derived from sales of advertising space on the spacecraft, delivery of branded materials to the target object, and use of video in advertising.

Technology companies may be the most attractive targets for licensing and sponsorship deals, although a broad approach to identification of potential partners should be taken. LunaCorp, for example, has attempted to finance various robotic lunar mission concepts through licensing and sponsorship deals with the likes of Mitsubishi and Radio Shack.[55]

Documentary film rights represent another potential source of revenue. According to the IMAX Corporation, the large-format space trilogy (*The Dream is Alive, Blue Planet*, and *Destiny in Space*) has grossed more than $250 million and has been seen by more than 70 million people worldwide.[56] At least seven other large format films deal directly with spaceflight or space science, some of which include footage shot in space from the Shuttle, *Mir*, the ISS, and various space probes. Media rights opportunities might include sale of exclusive rights to what may be the first high-definition video footage ever returned from deep space.

Another form of licensing involves licensing of the likeness of the NEO Miner platform or an ARPS Lander model as toys. NASA has licensed its Mars Exploration Rovers to Danish toy maker Lego, for example, and has signed a number of licensing deals for toys and models of the rovers.[57]

3.6. Longer-Term Markets

The key longer-term markets are those logical on-orbit markets that will inevitably emerge but which lack the infrastructure to be viable today. These potential orbital markets for NEO resources may be worth hundreds of billions within twenty to thirty years, but as noted above, it will be necessary to invest in orbital substantial new infrastructure before these markets truly become viable.

Volatiles. Volatiles may be the easiest products to extract and process, and the potential future orbital market could be enormous. Specific markets include water for use by the International Space Station and for future manned missions, rocket fuel for use in orbital tugs and other spacecraft, and feedstock to supply orbital fuel depots for refueling a wide range of craft in Earth orbit. As noted above, an infrastructure for processing and delivering NEO-derived fuel to orbit would fundamentally alter the economics of space travel beyond LEO. Early uses of asteroidal volatiles may be to provide in situ production of carbon monoxide for use in metal refining and potentially to produce rocket fuel for returning processed resources to Earth. Steam rockets using water derived from NEOs have been proposed[58] and advances in steam rocket technology might make this option feasible.[59]

It costs about $10,000 to deliver a kilogram of cargo to low-Earth orbit (LEO). As a result, systems studies have shown that the most expensive part of transferring payloads to geo-synchronous-orbit (GEO) is the fuel. A cryogenic propellant production and storage depot stationed in LEO could lower the cost of missions to GEO and beyond. In 2000 and 2001, studies[60] were conducted at the NASA Marshall Space Flight Center on the technical requirements and commercial potential for propellant production depots in low-Earth-orbit (LEO) to support future commercial, NASA, and other missions. Results indicated that propellant production depots appear to be technically feasible given continued technology development and that there is a substantial, growing market that depots could support.

Semiconductors. Semiconductor elements represent another potentially significant orbital market. Semiconductors include elements such as phosphorus, gallium, germanium, arsenic selenium, indium, antimony, tellurium. They are valuable for orbital fabrication of very large thin-film photovoltaic arrays. Production and return to Earth orbit could be a key enabler for a space solar power satellite (SSPS) industry. While the price per kilogram is much lower on Earth than for platinum and other PGMs, the cost of launching these materials into space makes space-based production and delivery to Earth orbit in support of an SSPS industry economically attractive.[61]

Other Markets. As an orbital infrastructure is established, there will be a need for many additional products and materials that can be derived from asteroid resources, including metals for building orbital structures and other materials to support in-space construction and manufacturing.

4. Enablers of NEO Mining

More than just the identification of potential near-term markets is required to make NEO mining viable. Many unique challenges requiring multi-disciplinary solutions must be overcome to make NEO mining a technical and financial reality. Fortunately, we have reached a point where key enablers have begun to come together from many different arenas to make meeting these market needs possible. These factors include growing interest and investment in space commercialization, advances in NEO science, the evolution of key enabling technologies, and new organizational approaches that make the development process more efficient and cost effective (Figure 11).

Figure 11. Enablers of NEO Mining

4.1. Space Commercialization

Space commercialization and space resource utilization have been linked in the public mind for decades. At least since Dandridge Cole and Donald Cox published their 1964 classic *Islands in Space*,[62] the idea that humans might someday tap asteroids containing precious metals worth trillions of dollars has surfaced from time to time. The 1970s and early 1980s saw discussion and analysis of lunar and asteroidal resource utilization, but these proposals were stifled by a lack of private investment and the failure to develop a viable commercial infrastructure. In addition, while NASA and its contractors have spent tens of millions on low-mass-throughput-ratio (MTPR) lunar extraction studies, little money has been spent on developing techniques for use on near-Earth asteroids. Furthermore, NASA planners have typically (and understandably) been locked in the habits and mindset of lobbying for high-profile government projects (e.g., Apollo, Space Shuttle, International Space Station, lunar base, Mars landing) and not those of the operators of commercial businesses trying to figure out how to best put the resources of the solar system to use at the lowest cost.

Today, the space development community is in the midst of a transformation from a government-led to a private, more commercially focused endeavor. This transformation is beginning to have a real impact on the aerospace industry and make room for innovative new commercial concepts and businesses. These changes are in part due to the efforts of groups of hobbyists and interested individuals have created what has come to be known as the “alt.space movement,” named for the Usenet newsgroup where much discussion and sharing has occurred about alternative and commercial space efforts. One of the most striking manifestations of this movement today is the birth of new private launch industry.

The private space community may be in much the same position the information technology sector was a generation ago. Private investment and a new commercial mindset are changing the dynamics of space development. Entrepreneurs bring a different perspective to the problems of space development. At the 21st National Space Symposium in Denver in April 2005,[63] Shashi Raval, Novariant’s CEO, noted that entrepreneurs "connect dots from many different fields" and bring an often hard-won realization that failure is a learning process from which progress can occur. He noted that many innovations are missed by gurus of industry asked whether a "Google-type" company will emerge from the space industry. Finally, he suggested that miniaturization of space hardware may enable thousands of new enterprises. Entrepreneurs will invent applications and enable markets that incumbent firms don’t see or appreciate.

As another means of spurring new entrepreneurial activity, several groups have also focused on using prizes as a tool to stimulate private investment in space. For example, the Ansari X Prize greatly invigorated the effort to build a successful new launch technology. Picking up on the success of the X Prize, Congress has just begun to fund a NASA program called the “Centennial Challenge” that will provide prizes for private achievement of a number of NASA objectives.

Most recent space commerce activity has been focused on the potential for space tourism. For example, Richard Branson has formed Virgin Galactic with Bert Rutan’s SpaceShipOne organization. Bigelow Aerospace is focused on space tourism and space hotel ventures. The interest in space tourism and sub-orbital flight has led to investment in a number of new launch companies, with some, like Space Exploration Corp. (SpaceX), poised to potentially have a real impact on the cost of sending payloads into orbit and beyond.

Space resource utilization has been widely discussed and studied, but little real development has been undertaken. Most proposals are built upon hugely expensive long-term venture to produce products that have only hypothetical future markets (e.g., helium-3 mining on the Moon, return of volatiles to Earth orbit for fueling of spacecraft, orbital assembly of space solar power satellites). Few efforts have been undertaken to develop prototype equipment for near-term missions. One notable exception in the space resources arena was the effort by SpaceDev to fly NEAP.

The current growth in the commercial space sector brings new approaches, it creates public and investor excitement, it brings new capital to the table, and it helps to generate credibility for entrepreneurs exploring novel space ventures.

4.2. Asteroid Science

This is a golden age for those with an interest in NEOs. Today, we know far more about them than we knew just a decade ago. Advances in our understanding of NEOs that enable us to better understand their commercial potential and plan successful missions include the discovery of nearly 3,000 new NEOs, enhanced understanding of surface characteristics and mineralogy, and extensive mission experience (including the landing of NEAR-Shoemaker on the near-Earth asteroid Eros in 2001).

Several robotic asteroid and comet missions[64] have been completed or are in the works, greatly advancing our knowledge of NEO resources and operating conditions (Figure 12).

Figure 12. Robotic Asteroid/Comet Missions

Object	Spacecraft	Year	Description
Phobos and Deimos	Various (including Mars Express)	1970s - 2004	Several Russian, US, and European Mars missions have also studied Mars' two moons which appear to be captured asteroids. ESA Mars Express is the most recent orbiter to study these two moons.
Comet Hailey	Giotto fly-by	1988	First comet closely observed by spacecraft. Found it was black because it was covered with a dirty, tar-like material determined to be "kerogen", CH2.5 polymer, similar to oil shale.
Comet P/Grigg-Skjellerup	Giotto fly-by	1990	Encountered the comet on July 10, 1992. The closest approach was 200 km at a relative velocity of 13.99 km/s. Eight experiments were operated and provided a wealth of data.
Gaspra	Galileo en route to Jupiter	1991	Entered asteroid belt, passing about 1600 kilometers from Gaspra. Pictures and other data collected revealed it to be a cratered, complex, and irregular body about 19 by 12 by 11 kilometers, with a thin dirt-like regolith.
Ida and Dactyl	Galileo en route to Jupiter	1993	On August 28, 1993, found Ida to be about 55 kilometers long and very irregular in shape. It rotates every 4.6 hours and also has a moon named Dactyl that orbits about 100 kilometers from the center of the asteroid.
Mathilde	NEAR en route to asteroid Eros	1997	Passed within 1200 km of main belt asteroid with extremely slow rotation period of 17.5 days on June 27, 1997, and acquired more than 500 images. First close observation of a C-asteroid.
Braille	Deep Space 1 fly-by	1999	Spacecraft flew past asteroid (9969) Braille on July 28, 1999, but camera problems limited the data received during this encounter.
Eros	NEAR orbit/landing	2000	Most extensive asteroid mission to date, orbited for a year and landed on this main belt S-class asteroid about 13 x 13 x 33 km in size. Extensive analysis of surface. Most detailed knowledge to date of asteroid.
Comet Borrelly	Deep Space 1 fly-by	2001	Spacecraft made a very successful flyby to within 2000 kilometers of comet on September 22, 2001.
Comet P/Wild 2	Stardust sample return	2004	Flew through the dust atmosphere of comet Wild 2 on January 2, 2004, imaged the icy cometary nucleus, collected dust samples, and will return these samples to Earth in January 2006 .
Comet Tempel 1	Deep Impact	2005	Will fire a 350-kilogram projectile into the comet, photograph the impact and analyze the fresh crater in order to develop a better understanding of comet structure and composition.
25143 Itokawa	Hayabusa (MUSES-C)	2005	Arrives at asteroid summer of 2005 and will orbit for about 5 months, making observations and collecting samples from the asteroid's surface. Will return to the earth summer of 2007.
Steins	Rosetta fly-by	2008	Will fly by the asteroid Steins on 5 September 2008 at a distance of just over 1700 kilometers. This encounter will be the first excursion into the asteroid belt by Rosetta on its way to its ultimate comet destination.
Lutetia	Rosetta fly-by	2010	Will fly by asteroid Lutetia on 10 July 2010 within about 3000 kilometers. This will be the second encounter of the asteroid belt on its way to its ultimate comet destination.
Vesta and Ceres	Dawn	2010	To be launched in 2006 to orbit Vesta and Ceres, two of the largest asteroids in the solar system. The two asteroids have very different properties and the mission is designed to compare and contrast them.
Comet Churymov-Gerasimenko	Rosetta orbit/lander	2014	Launched on March 2, 2004, the Rosetta spacecraft will rendezvous and land upon the surface of comet in late 2014. The comet's nucleus will be studied remotely and with the aid of a sophisticated lander.

While most of these missions have been high-speed fly-bys, they have still greatly enhanced our understanding of asteroid and comet structure and geology. In addition, they provide valuable experience and insights into building and operating successful asteroid missions. Most importantly, one of these missions, NEAR-Shoemaker, has provided not only extensive knowledge of surface structure and geology but invaluable data about the operational requirements for orbiting and landing on an asteroid.[65]

These missions along with Earth-based analyses and meteorite studies have provided us with a rich new understanding of asteroid geology. Both theoretical and observational studies suggest that many asteroids contain surfaces of finely granulated regolith produced by meteorite impact rather than pure, coherent rock surfaces. This result is important in contemplating sampling and refining of resources because a deep regolith would obviate the need to cut apart or crush chunks of coherent asteroid. While the depth of the regolith to be found on any specific asteroid is highly uncertain, analysis of Eros and radar studies of other asteroids have suggested depths ranging from a few meters to hundreds of meters.

NEAR-Shoemaker showed that Eros had numerous large craters and valleys that exhibited a pooling of regolith. Regolith may be more than 100 meters deep in some locations. While we cannot know for certain what surface conditions will look like on our target asteroid, we can hypothesize that there will be large craters and valleys containing deep regolith ponds. Even a relatively low density pool of regolith no more than 100 meters in diameter by approximately 20 meters in depth is enough to supply a lander with more than 250-thousand tons of loose material to process (assuming a low density of 1.6 g/cm3 – actual density may be considerably higher if the regolith is metal-rich). These locations are likely to be ideal locations for landing automated mining platforms to sort and process regolith.

Based on the NEAR-Shoemaker observations, scientists have developed laboratory experiments to help understand the evolution of the surface characteristics observed on Eros. For example, in a laboratory experiment, seismic shock waves (simulating surface impacts) were found to destabilize portions of the asteroid's regolith.[66] Though the computer model was not meant to show all the outcomes of regolith migrating down slopes, it does demonstrate a mechanism for creating slumps, avalanches, and the pooling of regolith in low areas. Like flour clinging to the inside of a bowl that is tapped, the regolith migrates slowly downhill after each significant impact. This model properly simulates the degradation and erasure of small impact craters, all features seen on Eros. Other laboratory research suggests that metals tend to “float” to the surface of asteroids due to cooling and outgassing.[67] Recent research[68] suggests that less abundant, smaller diameter metal particles, present in L and LL Chondrites, would tend to rise to the surface, whereas more abundant, larger diameter particles, present in H Chondrites, would tend to sink.

This combination of the space science missions, Earth-based discovery and analysis, meteorite studies, laboratory studies, and computer simulations and models enables the creation of an extremely rich understanding of asteroid geology and environmental conditions. These findings are essential to developing viable NEO mining concepts.

4.3. Technology Evolution

The continuing evolution of several key technologies makes the exploitation of NEO resources more feasible and less costly. New and evolving technologies enable not only new spacecraft capabilities, but also powerful new approaches to spacecraft and mission design. These technical developments include enhanced computing performance, advances in robotics and automated systems, new materials, superior photovoltaic cells and power systems, compact chemical resource processing technologies, inflatable aeroshells, and improved design tools (Figure 13).

Figure 13. Selected Technology Developments

Technology Development	Description	Implications
Robotics	▪ Improved robotic mining and movement systems; muscle wire and other high-power, low mass and low energy actuators	▪ Ability to remotely operate and mine without need for constant human control
Electronics and Microsystems	▪ Low cost and improved performance of microprocessors and storage technologies	▪ Much improved automation at reduced costs and the ability to collect and store vast amounts of data
Space Parachute/Ballute	▪ Lightweight, inflatable return technology	▪ Ability to deliver large payloads to Earth using little mass for fuel and aeroshell; ability to use aero-braking and aero-entry for return
New Materials	▪ Carbon nanofibers and advanced composites that are far stronger and lighter than steal	▪ Ability to reduce mass of spacecraft while improving performance
Mining Technologies	▪ Automated mining experience, development of space mining capabilities, ultrasonic milling tools and chemical reactors for refining	▪ Ability to produce marketable quantities of PGMs and other products using a compact and cost-effective platform
Quantum Dot Solar Technology	▪ Enables construction of more efficient and lighter photovoltaic solar power arrays for spacecraft	▪ Ability to produce the power required to operate mining and processing systems in an asteroid environment
Control and Automation Software	▪ Software that exploits far more powerful microprocessors	▪ Better automation, lower-cost development, improved quality control, and improved ability to repair systems
Mission Experience	▪ Experience building and flying low-cost space missions (e.g., asteroid missions, Clementine, Lunar Prospector) and "microspace" movement	▪ Ability to acquire tested tools and hire individuals with experience working on similar platforms
Design Software	▪ Significant improvement in design tools such as solid modeling and finite element analysis software	▪ Speeds design process and enables improved design quality without costs associate with building numerous prototypes
Low-Cost Launch Technologies	▪ Several firms are engaged in developing innovative new launch capabilities, driving down the cost of launch services (e.g., SpaceX, Xcor)	▪ Potential to dramatically lower the cost of a mission by significantly reducing the largest single cost of an asteroid mining mission

Technology issues present many of the greatest challenges to successfully and economically executing an asteroid mining mission. The prohibitively high costs of sending astronauts and potentially long communications delays require that all operations be highly automated. Automated machinery must work perfectly; even minor failures can cause mission failure. However, terrestrial mining experience with automation has generally been poor, and operations will be complex and hard on equipment.

New equipment will have to be developed and integrated. To handle industrial quantities of materials, bench-top processes are not sufficient. Developing industrial mining and refining processes will ultimately hinge on deployment of actual working equipment to learn what works and what does not. These systems will be different from those used in traditional robotic space science missions that essentially consist of one-of-a-kind instrument collections designed for generating very specific types of scientific data.

Another important area of technical innovation over the past 15 years has been the growing experience in launching lower-cost missions using commercial off the shelf technologies (COTS) and innovative organizational approaches. A whole micro-space industry has emerged building small satellites and space systems. Notable successes with these approaches have included Clementine, Lunar Prospector, and Deep Space 1.

The importance of engineering design of mining and extraction equipment cannot be overstated. There is a real possibility that mining equipment masses could be extremely compact, provided elegant ways are found to use the benefits of the unique space environment. Testing of equipment in the relevant environment is a critical step toward feasibility, and should focus on bringing reliability requirements to levels currently accepted by industry.

Little research and development has been undertaken into the capabilities required for NEO mining. In 1999, Zealey, Sonter, and a team at the University of Wollongong Department of Engineering Physics in Australia, worked to create a “reasonably realistic design” for an asteroid drill that could one day allow spacecraft to extract volatiles from a comet.[69] One aspect of this research required Zealey and Sonter to attempt to create low-density comet core simulants on which to perform mining experiments. The drill design was to include a penetrator with a thermal tip and explosive functionality that could bore, melt, and blast through cometary materials. It would also include a “cold finger” that would sit at the surface and collect steam created by the penetrator.

4.4. New Organizational Approaches

Advances in computing and telecommunications technologies have enabled new design processes and organizational approaches that have the potential to revolutionize the development of space systems. These new organizational approaches may ultimately be the most critical enablers of NEO resource utilization, serving as a catalyst for bringing together diverse advances in science and technology to economically create viable mission concepts.

The most important process and organizational innovation is likely to be the adoption of open source development approaches that enable projects to harness the capabilities of hundreds or even thousands of experts on a global scale. Open source is a form of decentralized production in which an information commons is cooperatively built, maintained, and evolved. The commons forms the primary basis of value from which individuals and firms draw and to which they contribute. Open source has emerged as a powerful engine of social and economic value creation whose methods can be harnessed to produce not only software, but a wide array of intellectual capital, including designs for the hardware and software and even complete mission concepts required to build innovative space ventures. In another paper,[70] I discuss this concept in greater detail

The adoption of open source design principles will mark the final step in a migration from the rigid, hierarchical design processes that have traditionally characterized space mission and spacecraft development processes. Today, one of the most important improvements related to design is a greater degree of collaboration within design teams. Underlying this shift is a fundamental change in how engineers view spacecraft systems. Traditionally, definition of a spacecraft was based on a hierarchical view of discrete systems that communicated through predefined interfaces. Today's definition envisions spacecraft systems as interrelated, dynamic, and reconfigurable.

By rethinking space mission and space system design, engineers have created an environment where collaborative design practices can flourish. Concurrent engineering and the corollary innovation, integrated product teams, are manifestations of collaborative design. These techniques place less emphasis on hierarchical team organization and linear approaches to design.

These new design approaches have been adopted at the same time that the use of computer-based tools has expanded rapidly, helping to control design costs and reducing the need for test models. Many of these innovations originated in the aircraft industry, where Boeing studies revealed that part interference (incidents of assembly parts overlapping each other) and difficulty in properly fitting parts together in aircraft final assembly were the most pervasive problems in manufacturing airplanes. To help alleviate this problem and reduce the skyrocketing costs of designing new aircraft, Boeing began investing heavily in the 1980s in three-dimensional computer-aided design/computer-aided manufacturing (CAD/CAM) technology. By the end of that decade, a single strategy for applying this capability emerged from numerous pilot programs which demonstrated the benefits of modeling airplane parts as three-dimensional solids in the CATIA (computer-aided three-dimensional interactive application) system. Developed by Dassault Systemes in France and marketed by IBM in the US, CATIA enabled Boeing engineers to simulate the geometry of an airplane design on the computer without the costly and time-consuming investment in physical mock-ups. Boeing used CATIA to design the 777, the first major aircraft developed using a comprehensive digital design process.

Today, even many small spacecraft builders use advanced design tools like CATIA. Although the capability is currently expensive, it saves money by reducing design time and enabling evaluation of design alternatives in a digital environment. Stand-alone design tools like CATIA can be limited, however, in their ability to interact with modeling and simulation systems. Advanced modeling and simulation systems began to reach a high state of fidelity in the early 1990s and are a natural evolution of independent computer-based design tools. The latest innovations have been in working to integrate the design tools with these systems to provide a more comprehensive virtual development environment.

Advances in simulation-based design (SBD) have proven to be well matched with collaborative approaches to design. One of the principal challenges of such approaches has been the difficulty of linking together advanced design tools and simulation models into a single, interactive environment. Such linkage requires creating interface standards that allow disparate models to exchange information and operate interactively. The Internet has been a powerful tool for creating these linkages. In the future, the SBD environment will likely be linked to data archives containing a common set of information on the parts and components used to build spacecraft. The result will be a digital design process where a widely dispersed spacecraft team can quickly close on a desired design solution and enter the fabrication and test phase with a high degree of confidence.

Virtual design environments are the state of the art, and spacecraft builders are only now starting to use them. As they gain acceptance, industry analysts predict significant reductions in design times and costs, while improving final component performance and reliability. The ability of a virtual environment to help the engineer visualize the effects of design changes is a key advantage of working in a simulated environment. Feedback is rapid, and other team members are available to resolve problems and make the required trades.

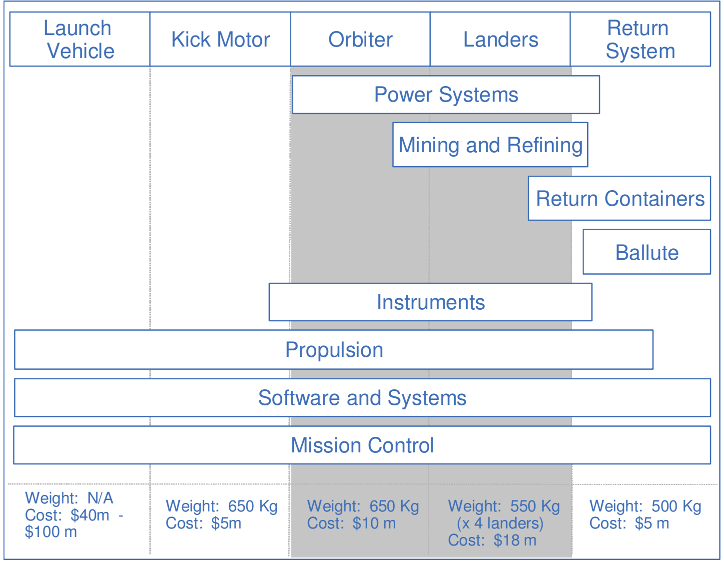
Virtual design environments enable new collaborative design approaches and will enable the migration of open source practices into the aerospace arena. First, there is a need for robust virtual design software that is accessible to a large body of potential users. Open source development practices can be used to create this software and enable a much broader user base than can now afford the high-end systems used by major aerospace manufacturers and NASA. Once the systems are in place, open source design processes can be used in distributed development efforts for individual space systems, spacecraft, and missions, enabling projects to harness the capabilities of hundreds and even thousands of contributors on a global basis.

Of course, new design and collaborative technologies should not, by themselves, be treated as silver bullets that we can expect to radically alter the cost of space mission and system design and manufacture. However, when combined with new organizational approaches, the ability to leverage increasingly robust COTS components, and an aggressive, multi-disciplinary perspective on system design and execution, significant innovations and cost reductions are likely. A secondary benefit of investment in these efforts to develop and operate asteroid mining platforms will be the ability to bring new ideas to space system development and drive significant innovation and change.

5. NEO Miner

The best way to bring our growing understanding of the asteroid resources opportunity together with evolving technical capabilities is to develop and refine a detailed mission design and business case. Based on extensive review of scientific and technical literature, the NEO Miner platform outlined here represents a first step towards defining a complete platform for cost-effectively mining, processing and returning NEO platinum as well as scientific samples and data to Earth (Figure 14).

Figure 14. NEO Miner Components



The two main components of the platform are an orbiter and a set of four identical landers. Other components include launch systems and an inflatable aeroshell recovery system used for aero-braking and cushioning the landing of return containers holding refined platinum, scientific samples, and hardened data storage systems used to deliver high-definition video footage and other data that would otherwise require too much bandwidth to transmit back to Earth.

Each lander consists of several major subsystems which together make up the Asteroidal Regolith Processing System (ARPS):

- Spiral screw anchoring system and robotic legs
- Magnetic rake for high-level regolith sorting
- Maneuverable auger extraction feed system
- Ultrasonic grinding mill
- Electrostatic beneficiation system
- Chemical processing unit
- Platinum deposition and return containers

The largest single cost is projected to be the launch of the platform by a commercial launch provider. The landers constitute the largest area of new technology development, requiring significant research, development, and testing of major systems and subsystems. Total launch weight of the platform is currently estimated at 4,250 Kg. Total cost (including launch) is estimated at between $75 million and $150 million.

5.1. Design Considerations

Based on our current knowledge of the asteroid environment, successful operations will require that NEO Miner address several unique environmental challenges that will ultimately drive much of the platform design (Figure 15).

Figure 15. Selected Asteroid Environmental Challenges

Parameter	Effects	Implications
Temperature Diurnal temperature swings (50-430K)	▪ Embrittlement, ▪ Lubricant efficacy ▪ Thermal Stresses ▪ Possible need for thermal control	▪ Mechanism Failure ▪ Motor Lockup ▪ Electronic Interconnect Failures
Gravity Gradients Weak Field (~.003 m/sec^2)	▪ Range of gravity's due to rotation and shape ▪ Low attractive properties	▪ Mechanisms must move slowly or be self-righting ▪ Low escape velocity
Chemicals/Minerals in Soil - Fines - Magnetic Fines - Oxidants/Acidic	▪ Accelerated wear ▪ Caking ▪ Attraction to magnets ▪ Thermal insulation, ▪ Abrasion ▪ Corrosion	▪ Mechanism Failure ▪ Motor Lockup ▪ Electronic Interconnect Failures ▪ Mechanism Failure
Terrain - Small Diameter (1 Km) - Craggy surface - Possible deep or no regolith	▪ Short distance to horizon ▪ Jagged cliffs and valleys ▪ Contamination of optics or solar cells	▪ Difficult path and communication ▪ Non-linear traversal ▪ Entrapment ▪ Obscuring ▪ Loss of power
Distance to Earth and Inclination	▪ Communications traversal distance ▪ Difficult communications. viewing angle	▪ Communication time lag ▪ Short communications windows
Rotation Rates (1-1,000 hr)	▪ Effect on insulation ▪ Effect on earth viewing time	▪ Power starvation ▪ Wide thermal cycle. ▪ Stalls between communications links
Vacuum Atmosphere	▪ Lubricant efficacy	▪ Motor/Mechanism Lockup
System Lifetime	▪ Time effects on materials	▪ Part wear-out
Uncertain Asteroid Properties	▪ Range of values on many parameters	▪ Difficult design process

Source: Adapted from Alberto Behar, et al., "Sub-Kilogram Intelligent Tele-robots (SKIT) for Asteroid Exploration and Exploitation," Space Studies Institute (1996), p. 5.

When operating on asteroid surfaces, the overriding considerations are the near absence of gravity and the strength of the regolith. Inertia, not overcoming gravity is the major effect to consider. On earth, equipment is held down by gravity, but on the surface of an asteroid, equivalent forces will have to be applied through a mechanism or mechanisms designed to attach the equipment to the surface. Mining machinery must be anchored to the surface and released material must be efficiently contained and recovered (using an enclosed screw conveyor or auger, for example). Containment will be important because escape velocity for small asteroids could be as little as 20 centimeters per second.

Securing equipment is relatively easy given rigid, competent, strongly bonded matrices – one can set anchors, drive in pitons, glue or adhere to the surface, or clamp against opposing surfaces. However, securing equipment is likely to be very difficult with low-strength or unconsolidated material, such as loose asteroidal regolith. If the regolith strength is low, the reaction forces created by excavation and collection activities will have to be spread over a relatively wide footprint.

Some proposals have called for surrounding the entire asteroid with a cable or membrane to provide the necessary anchor.[71] The types of NEOs targeted in the NEO Miner proposal will be too large for these approaches, so a system that provides sufficient anchoring for a lander in loose regolith is required. The concept proposed for the NEO Miner lander is to use a system of helical screws attached to pads on the ends of robotic legs. The lander will require at least three robotic legs, each equipped with these systems that can screw at least 1 meter into the regolith, providing a firm base for operation of the extraction and collection machinery located beneath the lander. The legs will require sufficient flexibility and range of motion to enable the lander to process several cubic meters of regolith without having to unscrew the anchors and move to a new location. If the regolith is deep and there are no major obstacles, the miner can process several tons of regolith in one location. The approach requires the assumption that there is regolith and it is loose enough and compressible enough for screw to penetrate. Extensive simulations and testing with simulants will be required to validate and refine this approach.

Another major design consideration is the need to limit power requirements as much as possible while generating sufficient power to operate the system. The orientation and rotation of a specific asteroid as well as the location of ore deposits will have a major impact on the ability to successfully complete mining operations. Extensive consideration must be given to developing novel approaches to reducing power consumption as well as to novel solar power systems, including potentially supplementing the lander's direct power generation through the use of power beamed from the orbiter.

Other design considerations include the requirements to make all processes and systems as simple and robust as possible and to ensure redundancy and adaptability. Systems must be flexible enough to work under a wide range of potential conditions. The platform will be unique in the history of space probes because its design is primarily driven by industrial mining objectives as opposed to scientific objectives.

5.2. Orbiter and Lander Systems

A platform that incorporates an orbiter with separate capabilities from the landers has several advantages. The orbiter can act as a communications relay for the landers as well as provide a dedicated platform for many traditional instruments such as imaging systems and spectrometers. It also can carry fuel and a return system that needs not be duplicated for each lander. A major challenge generated by this approach is the need to develop and operate automated rendezvous and docking systems in order to attach return containers from the landers to a return system that will remain attached to the orbiter.

The choice of multiple landers also provides several advantages. Most importantly, the system maximizes the chances of success by ensuring that should one or more landers fail, there are still systems capable of producing the samples and platinum required to generate an acceptable return on investment. In addition, if all four of the landers work as intended, they significantly increase the amount of regolith that can be processed in a given time period, increasing the revenue potential of the mission. Building multiple landers in parallel should also help to reduce cost of each individual lander. The major disadvantages to this approach are likely to be the increased complexity of operations as well as the need for a larger and more costly launch system in order to support the greater size and weight the use of this system entails.

5.3. Extraction and Processing Systems

The truly novel portion of the platform is the highly integrated, automated extraction and processing system. In contrast to this proposed system, the terrestrial PGM production processes involving large-scale mining of ore and the subsequent separation of one PGM metal from another (Figure 16).

Figure 16. Terrestrial Platinum Production Process

Parameter	Mining	Flotation	Smelting and Converting	Base Metal Refining	Precious Metal Refining	Total
Percent of Total Cost	65-76	9-12	6	7	4-5	100
PGE Grade (grams/ton)	5-6	100-600	640-6,000	30-60%	>99.8%	N/A
PGE Recovery (%)	N/A	80-90	95-96	>99	98-99	75-85
Grade Ration Increase	N/A	30-80	20	75	2	200,000
Processing Time (days)	N/A	2	7	14	30-150	Up to 170

Source: Lonmin Plc, Geology of the Bushveld Complex, 2003.

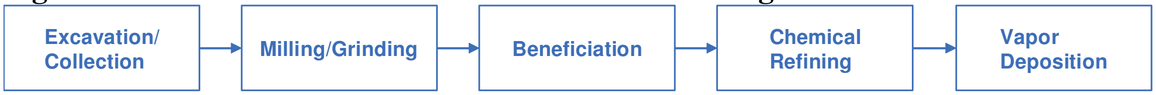
Current platinum mining and refining practices require about 10 tons of ore and a five-month process to produce a single ounce of platinum. Like most terrestrial mining processes, platinum production requires large investments in mining and processing equipment and the people to operate that equipment. Developing a new mine can cost as much as $1 billion, not including ongoing operating and refining costs.[72]

In addition, using today's most cost-effective methods, platinum production is a toxic enterprise, requiring tremendous amounts of chlorine, ammonia, and hydrogen chloride gas, which are all released as part of the process. Large amounts of effluents are left at the end of the process – several hundred pounds of toxic effluents per grain of platinum and other PGMs, including metals such as iron, zinc, nickel, as well as other metals that are part of the ore but not commercially viable to extract. The process also generates harmful sulfates. While major producers are now using more environmentally-sensitive means to mitigate pollution, the sheer volume of material involved and the minute quantity of valuable PGMs per ton of ore mean that terrestrial production processes inevitably harm the environment.

A robotic asteroid mining platform will use a radically different process. If the compositional data discussed in Section 2 is correct, the robotic miner will be starting with a grade of platinum group elements that is as high as that at the end of the third stage of the terrestrial production process. This also suggests that if an adequate approach to returning very large quantities of unprocessed material to Earth for processing could be developed, then many of the complex processing steps to be integrated into the NEO Miner platform would not be necessary. This approach deserves further study.

The extraction and processing that the automated platform integrated into each lander must perform consists of five steps (Figure 17).

Figure 17. Asteroidal Platinum Extraction and Refining Processes



A major challenge for asteroid mining is to miniaturize and integrate these processes into an automated platform that is capable of reliably operating in a near-zero-gravity environment under conditions of extreme heat and cold using as little power as possible.

A general design driver for this process is the amount of mass that must be processed in order to produce an economically viable amount of finished product. This quantity will vary dramatically based on the mineralogy and composition of the specific regolith that the lander is processing. However, the high specific value and the high grade of deposits anticipated mean that the mass to be handled and recovered to deliver an acceptable return on investment may not have to be large.

A rule of thumb for considering this requirement is the mass throughput ratio (MTPR), the ratio of finished produce produced to the mass of the production equipment. The mass of mining equipment, processing equipment, and power supply required for generating an output of 10 tons of platinum over a period of six months may be quite small, depending on the assumed MTPR and on the assumed power to mass ratio of the power system. Sonter notes that the daily MTPR for a number of different types of traditional materials handling and processing equipment is roughly a factor of 500.[73] So, conservatively positing a daily MTPR of the combined plant at a factor of 250, suggests that the equipment mass for handling 25,000 tons of regolith in 200 days, to extract 10 tons of platinum, could be something under half a ton. These estimates provide an indication of what engineers can reasonably aim for.

Extraction/Collection. A magnetic rake is used to provide initial, high-level sorting of metallic from non-metallic regolith. Assuming that the quality of the regolith is uneven, the magnetic rake system can be equipped with sensors and manipulation tools that enable the lander to sort regolith and focus on the highest-value regolith. Mounted beneath the main body of the lander in a highly maneuverable rig is a steerable, enclosed auger system used to collect finer-grained regolith from the surface and move it into the milling system. The magnetic rake or the auger system may also be equipped with an ultrasonic or laser drilling system to break up or loosen hard-packed regolith for collection by the auger. Use of the auger overcomes limitations of low-gravity environment by enclosing the regolith and enabling it to be force fed into an ultrasonic grinding mill.

Milling/Grinding. Comminution is the process of separating metals from non-metals and entails the size reduction of rocks and regolith by crushing and grinding. Crushing operations are size reduction operations on rocks and fragments greater than one centimeter in diameter. Because the vast majority of the regolith collected with the auger system is likely to be below one centimeter in diameter, the use of a crusher is not indicated. Grinding operations are performed on rock fragments of less than one centimeter diameter. While there are several potential options for milling the regolith, an ultrasonic grinding mill appears to be the optimal choice. Ultrasonic grinding mills impart the fragmentation energy to feed-stream particles through a ceramic transducer operating at high frequency. Rapid oscillations are used to crush feed material to the desired size. These mills require significantly less energy than conventional grinding techniques. No fluids are used and vacuum operations should present no problem. While limited gravity will affect the design of feed mechanisms, operation should otherwise be normal.[74]

Beneficiation. Next, the milled material must be processed to separate the desired metallic materials from other materials that are also contained in the matrix. Electrostatic separators provide an efficient means for extracting ferrous material from dry, bulk products. The end result is purified, mostly metallic product ready for further processing. The gangue (commercially valueless material remaining after ore-mineral extraction from the rock) is discarded. The absence of water and atmospheric gases is conducive to electrostatic separation techniques that separate particles on the basis of electrical conductivity or dielectric properties. Spatial separation of particles having differing electrical properties is performed by deflection or attraction of charged particles during transit through an externally applied electrostatic field.

Reduced gravity will affect the design of such units in terms of electrostatic field strength, spatial geometry, and feed-mechanism design, but overall this technique should also be highly adaptable to asteroid mining. Though electrostatic beneficiation is commonly used at mines on Earth, it would work even better in the low-gravity vacuum environment found on an asteroid surface. The vacuum of space means no air turbulence in the drop chamber. Air does not tolerate electric fields as well as vacuums do, enabling electric fields to be ten times stronger in a vacuum. In space, there is no moisture to make grains stick together. Moisture also alters the electrical conductivity of minerals and reduces the differences between them; hence, on Earth, the material often must be roasted before beneficiation. The asteroidal micro-gravity dramatically slows the fall of the material through the electric field, greatly enhancing the separation. A centrifuge can be used to create artificial gravity of any sensitivity.

Chemical Refining. There are at least two routes to integrated chemical refining and vapor deposition of the refined ore, but each will require significant additional research and development.

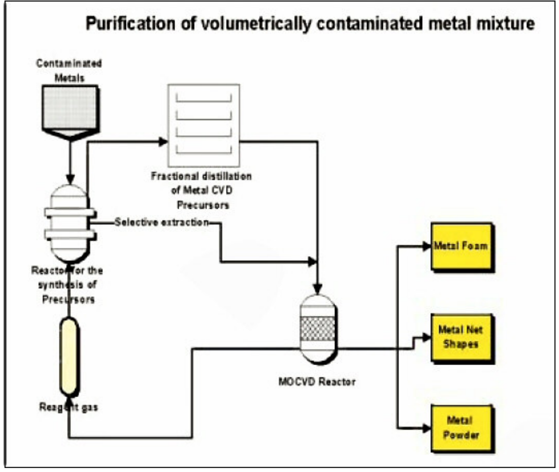
Lewis and Hutson[75] advocate a carbonyl extraction process for refining these materials from asteroids. The carbonyl vapor-metallurgical process requires insertion of the metallic fraction into a suitable digestion chamber where the digestion of the metals will occur. This is a low temperature/atmospheric pressure process, thus reducing the expensive conventional high energy and high pressure or vacuum processes generally related with metal beneficiation. A gaseous carbonyl extraction of the metals offers direct recovery of unaltered inclusions and relatively simple routes to elemental separation of solutes at low process temperatures. The only reagent required is gaseous

CO, which is readily produced by heating almost every known type of meteoritic material and can also be recycled within a closed-loop system. This process involves CO gas being passed through the material at 1 to 1,000 atmospheres pressure and 100°C temperature. Under such conditions, iron, nickel, and several other metals react to form a gaseous carbonyl compounds. Examples include, iron pentacarbonyl ($Fe + 5CO = Fe(CO)_5$ (gas)) and nickel tetracarbonyl ($Ni + 4CO = Ni(CO)_4$ (gas)). These gases may then be condensed and the metals deposited. The residue from the carbonyl extraction of native ferrous metal alloys is very rich in cobalt and platinum group metals. The cobalt may in turn be separated from the platinum-group metals by very high-pressure extraction with CO, by extraction with CO-H2O mixtures as the carbonyl hydride, or by wet chemical techniques. Lewis notes that this process has been used commercially on Earth for a century and is readily adaptable to space.

Lewis and his colleagues have made some progress towards developing a carbonyl processing system for use in space. Professor Subra Muralidharan at Western Michigan University has collaborated with and built upon work by Lewis and other in a series of projects to explore various aspects of metal extraction from asteroidal material (using meteorites).[76] This work has demonstrated reproducibility of reaction conditions and robustness of the reactor and also determined that there are vast differences in the reactivities of the meteorites and chondrites which the work could not readily explain. The ultimate goal of this research was to create (with Lewis) a flight prototype of a carbonyl processing unit.

Other chemical-based refining processes for platinum group metals exist. Kovtun, et al.,[77] describe a chemical vapor metal refining (CVMR) process for the extraction and separation of PGMs is a simple and economical alternative (Figure 18).

Figure 18. Chemical Vapor Metal Refining Process



Source: S.N. Kovtun, M.F. O'Meara, N. Victor, and D.S. Terekhov, "Chemical Vapour Metal Refining (CVMR) of Platinum Group of Metals (PGM)," Metallurgical Plant Design and Operating Strategies Sydney, NSW, April 15–16, 2002

The CVMR process is based on the formation of volatile metal compounds, followed by extraction and thermal decomposition, producing pure metals and reagent gases.[78]

In the case of PGMs, CVMR does not use CO, and hence, the process is quite different from the carbonyl process previously attempted by a number of organizations and test facilities. CVMR extracts PGMs via synthesis of trifluorophosphine complexes at low pressures and low temperatures (80 to 100°C). According to the authors, these two facts alone make the process highly economical, compared to other methods available.

The CVMR processes use a closed-loop method that recycles the reagents. None of the processes have any liquid waste, except in the cases where slurry is used as feed material; the solid waste, which consists of residues, after the pure metals have been extracted, is collected in the system. Gases used in the process are generally recycled. The CVMR processes can produce all of the following products on demand: powders, foams, net shapes, pellets, ingots. The final product form does not significantly change the design of the extraction system. While it is uncertain whether this process can be miniaturized and modified for use in an automated plant as part of the ARPS system, it requires further investigation as a potential alternative to carbonyl processing.

Vapor Deposition. The final platinum-production step is the deposition of pure platinum on mandrels in a return container. Each NEO Miner lander is equipped with an inflatable container that can be docked with containers from other landers and mated with the return system on the orbiter. Because of platinum's extremely high density (21.45 tons/m^3), a container large enough to transport several tons of refined platinum can be quite small in volume. Each return container will also include a hardened data storage system for returning terabytes of data as well as facilities for storing and protecting scientific samples for study by mission scientists and for sale to third-party buyers.

5.4. Return Containers and Ballute Technology

One final challenge is the cost-effective return of processed resources to Earth for sale. A major energy cost of the return mission is to decelerate the payload so as to achieve Earth-capture. Fuel requirements for propulsive braking and capture into orbit or for atmospheric entry render many asteroid resource concepts impractical.

There are various options for reducing velocity from hyperbolic to a bound planetary orbit upon return. One method is to rely on propulsive braking using propellant carried to the asteroid and back or by using asteroid-derived propellant. This is the simplest approach, but it is undesirable because it either adds additional fuel to the mass of the payload sent to the asteroid or it reduces the quantity of material that is returned to orbit and requires an additional system for producing asteroid-derived propellant in.

A second option is to rely on aero-braking or aero-entry using an Earth-fabricated aero-brake. A traditional aero-brake would likely require too much mass too make it viable. Some engineers have proposed in situ construction of an aero-brake from asteroidal materials, although this would appear too complex of a task given current robotic systems.

Yet another option is to use lunar fly-by to remove hyperbolic Δ-v will naturally insert the returning craft into highly elliptical Earth orbit (HEEO) with no stress on the payload and no consumption of propellant. Navigation and timing constraints must be met to ensure the requisite low altitude pass over the Moon at the proper time in its orbit to provide maximum velocity loss. A maximum velocity reduction of 1.5 km/sec. has been quoted for a single lunar flyby. This corresponds to an object returning on a transfer orbit of Q = 1.25 AU, from an aphelion mining mission; and an object returning on a transfer orbit of q = 0.83 AU from a perihelion mining mission. For this type of option, the most desirable targets for lunar flyby capture are those asteroids with aphelia less than 1.25 AU or perihelia more than 0.8 AU.

Given these constraints, ballute technologies provide an intriguing solution to this problem, potentially negating the requirement for propulsive braking or complex and time-consuming orbital maneuvers to use the gravity of other bodies to place a return container into Earth orbit or to enable entry into the Earth's atmosphere for recovery on the ground. Ballutes are inflatable structures designed to act as aero-shells and parachutes. There relatively compact, lightweight systems duplicate the functions of a much heavier aero-shell.

The most mature ballute technology available is the Inflatable Re-Entry and Descent Technology (IRDT) demonstrator originally developed by NPO Lavochkin as part of the Mars-96 mission to support entry and descent of a Mars penetrator lander (Figure 19).

Figure 19. Ballute

Source: L. Marraffa, et al., "Inflatable RE-Entry Technologies: Flight Demonstration and Future Prospects," ESA Bulletin 102 (August 2000).

The IRDT employs an inflatable envelope able to withstand the extreme hypersonic flight environment of re-entry. It provides a lightweight, cost-effective aero-shell that can be used for aero-braking and aero-entry. Use of the ballute system will enable aero-braking and aero-entry concepts that should greatly reduce fuel requirements. The ballute system also enables precision landing of the heavy payload in an unpopulated recovery area. The inflatable technology offers great advantages due to its low volume and mass.

As noted in the previous section, the return containers incorporated into each lander are designed so that they can be docked and mated with the ballute system on the orbiter for return to earth. These containers provide mandrels for depositing platinum as well as chambers for secure return of samples and hardened data storage systems.

Use of this type of return craft enables precise delivery of a large payload including unprecedented quantities of data. Since the cost of data storage hardware is decreasing very rapidly, terabytes of data can now be returned in compact, hardened data storage systems contained in each of the return containers. Data can be mirrored between data storage systems in each container mitigating concerns about the failure of or destruction of the data in one or more of the containers during re-entry and landing. This capability will make possible the return hundreds of hours of high-definition video plus other data that would otherwise be impossible to return due to limited bandwidth for deep space communications. As noted in Section 3, the ability to return so much high-definition video is a source of revenue by itself. It also will enable engineers to study processes and telemetry as never before in order to re-design and improve processes for future missions. Finally, it can be used as a powerful marketing tool.

5.5. Power Budget and Solar Power Options

Generating adequate power for each lander to perform extraction and processing is another critical challenge. Power issues are driven by three major constraints. First, rotation of asteroid limits solar power generation on the surface. Second, there are potential limitations due to distance from the sun (effects mission design). Third, power requirements may be significant given the tasks performed by the lander.

Addressing these power issues require a two-pronged approach. First, significant research will be required to choose technologies that require as little power as possible. Reducing power for the extraction and processing efforts will be critical, requiring an intense focus on power consumption and integrating technologies that are very efficient. Second, new solar cell technology may significantly improve power generation. One of these technologies is quantum dot technology which appears to offer significant improvements over the performance of traditional photovoltaic cells.[79] Another option to be explored will be the efficacy of taking advantage of the extremely low gravity by placing solar panels on a mast or tether that enables them to be positioned high above the lander in order to ensure maximum access to the sun. Yet another option to be explored is the potential of beaming power from the orbiter to individual landers on the surface of the asteroid. Finally, nuclear power is the ideal long-term power solution, but it is neither economically nor politically viable for an initial mission.

5.6. Teleoperation and Automation

Another area requiring significant innovation is teleoperation and automation. Distance, rotation, new and untested equipment, unpredictable processes and activities all create challenges for operation of the platform. Communications delay is a major constraint given the potential distance and orbital characteristics of the target object. In addition, the use of multiple landers and an orbiter and docking required for return of finished product calls for the use of automated rendezvous and docking capabilities (e.g., Russian technology utilized in Progress spacecraft).

When problems arise, there will be a need for automated systems to detect problems and fix them in real-time. The platform will have to make extensive use of novel self-diagnosing and self-healing systems that incorporate fault detection isolation and recovery (FDIR) logic for autonomous operation. These systems will have to be able to address the severe challenges of operating continuously in a harsh environment over extended periods of time. These automated operations will be further complicated by the presence of multiple landers.

5.7 NEO Miner as a Disruptive Technology

When viewed in the context of traditional mining practices, the NEO Miner platform represents a classic example of a disruptive technology.[80] Disruptive technologies bring to the market very different value propositions than have been available previously. Generally, disruptive technologies initially underperform established products in mainstream markets, but they have other features that a few fringe (and generally new) customer value. Products based on disruptive technologies are typically cheaper, simpler, smaller, and frequently more convenient to use.

Neo Miner does not represent an incremental improvement to traditional resource production processes. It is a radical departure that is smaller and cheaper than a traditional mining operation and many, in some ways, be considered inferior. However, it has the potential to be highly disruptive of traditional mining methods.

As a disruptive technology, initial success is likely to fuel rapid improvements in performance and reductions in cost. The use of multiple landers with modular components is a powerful tool for risk reduction that enables the capture of economies of scale that can dramatically drive down the cost of this equipment over time. Once successful operation of the platform is demonstrated, it will become viable to build landers using assembly-line production processes and deploy multiple missions to one or more asteroids simultaneously, producing significant marketable quantities of resources for sale in terrestrial markets and for use on orbit. In addition, it will be possible to update the NEO Miner platform in each successive generation based on data and experiences gathered through each deployment. This could enable dramatic improvements in the functionality of the landers as well as drive down their cost to a point that dozens of missions with hundreds of landers can be launched. This approach has the potential to dramatically drive down the cost of utilizing asteroid resources on Earth and beyond.

A key design objective is to ensure that the platform is highly modular so that pieces are interchangeable and can be flexibly used for various types of missions. For example, if it is being used to return volatiles or other raw materials for use on orbit, additional inflatable return containers could be transported to an asteroid where robotic landers had tapped a particularly rich site and the orbital mechanics made return flights economically viable.

6. Risk Factors

While risk is inherent in any space venture – especially one requiring the development and integration of novel technologies – most of the major risks associated with the NEO Miner mission concept can be identified and strategies implemented to manage and mitigate them (Figure 19).

Figure 20. Summary of Major Risks and Mitigation Strategies

	Examples	Consequences	Mitigation Strategies
Technical	▪ Failure of launch vehicle ▪ Mechanical failure of space systems ▪ Failure of return vehicle	▪ Failure to reach target asteroid ▪ Inability to mine or process ore ▪ Failure to return samples or processed product for sale	▪ Institute aggressive testing and quality assurance program ▪ Over-engineer critical systems ▪ Launch insurance
Scientific	▪ Limited marketable minerals in asteroid regolith ▪ Surface not conducive to mining	▪ Inability to mine or process marketable ore ▪ Failure to collect adequate data or samples	▪ Design for wide range of potential surface conditions ▪ Select target carefully to maximize chances of favorable conditions ▪ Build in flexibility to move to second target if initial is inadequate
Market	▪ Insufficient market for scientific data ▪ Significant decrease in platinum demand and price	▪ Failure to generate adequate revenue despite successful operations	▪ Focus on multiple revenue streams ▪ Design mission to be profitable within a wide range of potential market conditions
Political	▪ Licensing and property rights issues ▪ Export controls ▪ Safety regulations regarding product return	▪ Inability to launch ▪ Lack of ability to contract with foreign launch providers ▪ Inability to land return containers with product	▪ Government relationship program ▪ Early focus on addressing potential political risk issues ▪ Aggressive engagement of relevant government organizations from the beginning

The most significant risks involve the novel technologies used in the lander and mining system and the potential that the target asteroid will be unsuitable for mining due to poor ore quality or difficult surface conditions. Through the use of redundant systems, extensive testing, and the development of highly flexible mission designs, these major risks can be effectively managed and mitigated. A successful venture will require adoption of aggressive and comprehensive risk management systems to ensure that all risks are identified and that appropriate steps are taken to mitigate them.

6.1. Technical Risk

Several key technical risks must be addressed. Some of these are the traditional technical risks faced by any space mission. Others are novel risks resulting from the requirement that considerable new technology be developed and integrated to enable the envisioned mission.

Traditional technical risks include the potential for launch failure. This risk is managed through contracting with a reliable launch partner as well as through the use of launch insurance. There are also technical risks associated with the systems in the orbiter and the landers. Some of these risks can be largely mitigated through the use of simple, proven technology. Other risks are more difficult to manage because they entail the use and integration of novel technology. The landers, in particular, incorporate new technologies. For example, the robotic systems used to anchor the landers will be novel. While tested in simulants and through computer models, the first test of this technology in an actual working environment will be in operation. The computer systems and other systems required for autonomous operations and for teleoperation will have to function with significant time delay. Another critical technology will be the automated rendezvous and docking technology required to deliver the return containers to the orbiter for the return to Earth.

The extraction and processing technology at the heart of the ARPS system is one of the most critical functions of the entire platform, and while it will be possible to perform extensive computer and physical simulations on Earth, one can assume that every asteroid has unique conditions for which it may not be possible to prepare. Additional challenges for the ARPS system include uncertainty about the ability to sufficiently integrate the required components while still producing required mass throughput. It will be essential to develop flexible systems capable of operating under many different potential environmental conditions.

Power systems are another significant technical risk. Experience operating photovoltaic cells in an asteroid environment is very limited, and there are likely to be challenges associated with distance from the sun, dust, and the rotational period and orientation of the asteroid. The availability of quantum dot technology and whether or not actual performance will meet projected performance is another uncertainty.

The return technology creates significant risks due to the novel use of the ballute to land a heavy payload as well as the uncertainty around the use of the ballute for aero-braking and aero-entry.

In addition to specific risk-reductions strategies directed at specific functions and technologies, there are also several more general risk management strategies that any asteroid mission will have to pursue. For example, the growing wealth of mission experience means that mission planners will be able to draw from and consult with teams that have built and flown NEO fly-by and lander missions and learn from their experience. In addition, while no one has yet built and flown an industrial mining and ore processing system, there is a vast body of mining knowledge and experience that mission planners can draw upon to identify and mitigate risks.

Other more general technology risk management strategies include purchase and maintenance of relevant insurance, rigorous testing and quality assurance programs, extensive use of models and simulations, and the development of redundant systems

6.2. Scientific Risk

The term “scientific risk” refers here to the set of uncertainties that arise from our incomplete scientific knowledge about NEOs and their surface environments. This is the risk that results from our limited knowledge of actual resource abundance and distribution and the precise environmental conditions under which these resources will need to be extracted and processed. It is not possible to know for certain how much platinum there is, what condition it is in, and what environmental constraints the platform will have to operate under until we (or our robotic probes) actually go there and investigate. Specific examples of these risks arising from uncertainty about asteroid geology and metallurgy include poor ore quality; solid surface or low-strength, unconsolidated material unsuitable for anchoring; solid surface unsuitable for excavation and collection; and rotation/access to sun for solar power.

Without a sample returned from an asteroid, the evidence of mineral concentrations remains circumstantial. Detailed asteroid reconnaissance by spacecraft has dramatically improved geologic models but has only been carried out recently for a handful of asteroids. Spectral analysis of data from telescopic observation can sometimes be used to infer general geological characteristics such as bulk composition for newer asteroid discoveries.

The physical properties provide key constraints on which asteroids can be mined.[81] Factors such as size, shape, spin rate, spin state, orientation of angular momentum, and whether the asteroid has a binary, are all important in deciding the strategy for close proximity operations. Engineering constraints will make it necessary to avoid asteroids that are smaller than 200 meters in diameter because they tend to have high spin rates and are more likely than large asteroids to be regolith-free. It is possible to design a mission to satisfy most of the expected conditions, but a mission that could deal with the different situations that may be present at each asteroid will have to be very sophisticated.

To address these scientific risks, there are several strategies. First, it is essential to make use of extensive earth-based analyses of potential targets (e.g., spectroscopy, radar imaging) to identify as best as possible those targets with desired mineralogy and surface requirements. This will require assembly of detailed data on target asteroids and sophisticated computer models that include size, orientation and rotational data gathered from radar studies. Second, it will be necessary to design a highly flexible platform that can perform under wide range of conditions. Finally, when permitted by orbital mechanics, mission planners should design missions so that platform can move to secondary or tertiary asteroids if the initial target proves inadequate upon closer examination.

6.3. Market Risk

Market risk is the uncertainty about the market demand and price for key products produced by the mission. For example, while there is anecdotal evidence based on the SpaceDev NEAP effort that suggests there is a market for scientific data and sample returns, without further research, no one can know for sure how firm the market interest really is or the dynamics of this market.

More critically, while some academic studies have examined the potential impact of asteroidal platinum on terrestrial platinum prices, the actual market impact will be difficult to gauge until someone successfully executes a mission and returns product for sale. Some work has been done on the potential impact of asteroidal platinum on terrestrial markets. Kargel[82] did pioneering work in this area, and more recently Blair[83] has done additional analysis exploring the potential impact of asteroidal platinum on terrestrial platinum prices. Blair concludes that "[p]rovided other products provide additional economic incentive, platinum from asteroids appears to have the potential to significantly alter the long-term characteristics of the terrestrial platinum market."

Other market risks manifest themselves in the planning stage. These include uncertainty about the number and willingness of organizations purchasing scientific data and samples as well as uncertainty about the market for entertainment/branding connected with mission.

6.4. Political Risk

Political risk is an important and often overlooked component of any space venture. Political considerations have a significant impact on launch options and costs. Export license issues severely limit the ability to launch sophisticated US-developed technology in some countries. In addition, export and import licensing issues are likely to significantly impact the use of technologies developed in other countries, especially many Russian technologies that may prove important components to this effort.

Launch issues include requirements for and costs associated with launch permits as well as export restrictions that may limit ability to contract with low-cost foreign launch providers.

Another critical consideration for the mission envisioned here is the impact of safety considerations on the planned use of a largely untested aero-braking and aero-entry technology to deliver a heavy payload to a surface landing. Additional risks attached to the return of product include potential regulation and concerns about ability to land large payload safely without danger to populated areas. Other potential issues that may arise and must be addressed with authorities are potential concerns about contamination and proper quarantine of returned materials.

A political risk that has been written about extensively but remains unresolved is uncertainty about property rights and ownership issues.[84] There is no controlling legal precedent addressing ownership of target asteroids and their resources. When Jim Benson of SpaceDev first proposed the NEAP mission, one of his stated objectives was to claim mining rights in order to test the legal issues governing ownership. Benson hoped that by staking an ownership claim on the asteroid NEAP landed on SpaceDev could establish a precedent for private property rights in space.[85]

One final area of political risk is concern over use of nuclear power which effectively precludes nuclear options for propulsion and platform power generation.

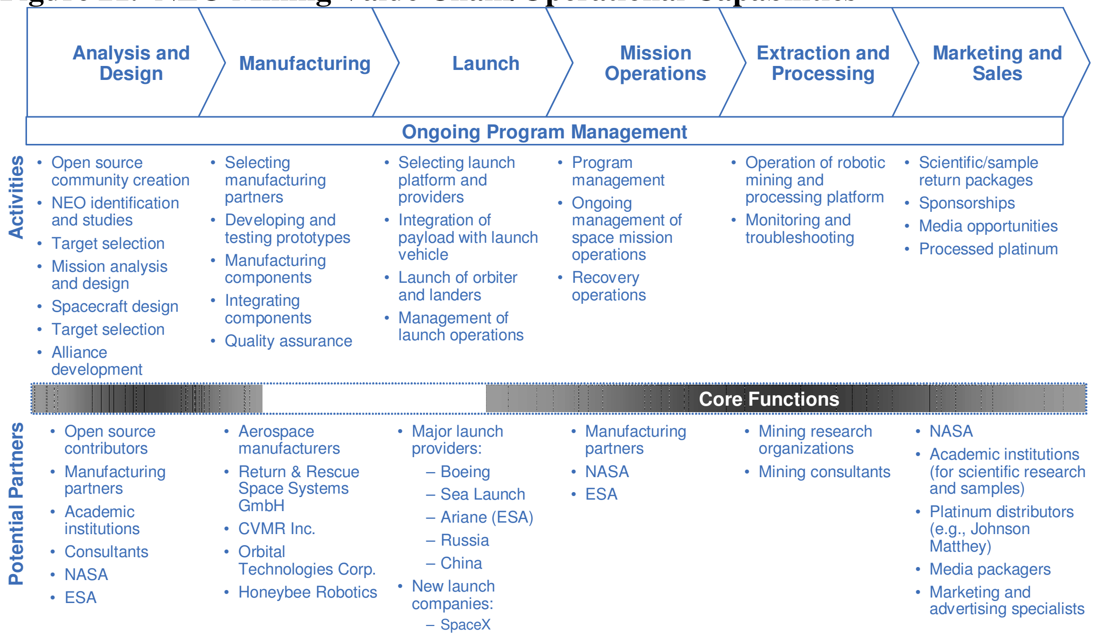
7. Operational and Financial Considerations

What capabilities and levels of investment are required to build and operate the platform described in Section 5? Is it financially feasible to build and fly such a platform given today's technology and business environment?

7.1. Functional Capabilities

Successfully executing an NEO mining mission will require the development of a strong set of core competencies both internally and through partnerships. An organization capable of successfully executing an asteroid mining venture will require a broad set of capabilities within six functional areas as well as strong program management skills across all of the functional capabilities (Figure 21).

Figure 21. NEO Mining Value Chain/Operational Capabilities



	Analysis and Design	Manufacturing	Launch	Mission Operations	Extraction and Processing	Marketing and Sales
Ongoing Program Management						
Activities	• Open source community creation • NEO identification and studies • Target selection • Mission analysis and design • Spacecraft design • Target selection • Alliance development	• Selecting manufacturing partners • Developing and testing prototypes • Manufacturing components • Integrating components • Quality assurance	• Selecting launch platform and providers • Integration of payload with launch vehicle • Launch of orbiter and landers • Management of launch operations	• Program management • Ongoing management of space mission operations • Recovery operations	• Operation of robotic mining and processing platform • Monitoring and troubleshooting	• Scientific/sample return packages • Sponsorships • Media opportunities • Processed platinum
Core Functions				Core Functions	Core Functions	Core Functions
Potential Partners	• Open source contributors • Manufacturing partners • Academic institutions • Consultants • NASA • ESA	• Aerospace manufacturers • Return & Rescue Space Systems GmbH • CVMR Inc. • Orbital Technologies Corp. • Honeybee Robotics	• Major launch providers: – Boeing – Sea Launch – Ariane (ESA) – Russia – China • New launch companies: – SpaceX	• Manufacturing partners • NASA • ESA	• Mining research organizations • Mining consultants	• NASA • Academic institutions (for scientific research and samples) • Platinum distributors (e.g., Johnson Matthey) • Media packagers • Marketing and advertising specialists

It will be essential to build a dedicated business organization focused on key functions in the value chain. The analysis and design capability is likely to be highly distributed. Manufacturing is likely to be outsourced to a number of contractors. Launch services will be purchased from a third-party launch-services provider. Besides raising capital and comprehensive program management, core functions of the sponsoring organization are likely to be mission operations, management of the mining and processing function, and marketing and sales.

Analysis and Design. Space mission analysis activities focus on the preliminary definition of space missions, in order to determine the optimal mission profile to achieve a given objective. In particular, mission analysis addresses the study of launch windows, ascent and re-entry profiles, orbits and trajectories, as well as navigation, guidance and control aspects. The development of specific algorithms and software tools provides comprehensive analysis capabilities to cope with these mission analysis activities. Here, we also use the term more broadly to encompass research and development activities required to create and integrate new technology as well as business case development and refinement.

Manufacturing. Construction of the initial lander and orbiters will likely be undertaken by third-party manufacturing partners specializing in space systems and spacecraft manufacturing. This is an increasingly competitive marketplace, with both incumbent and new entrants rapidly adapting new manufacturing practices that should reduce the cost of constructing the platform.

Launch. The launch process entails sizing and selection of the launch vehicle(s) as well as the operations involved in mating the platform to the launch vehicle(s) and the actual launch itself. This is another activity which will be conducted by third-party partners.

Mission Operations. These are a collection of activities performed by operations teams during the flight phase of the mission, together with the operations design activities they perform pre-launch, including development of a mission operations concept, policies, data flows, training plans, staffing plans, and cost estimates. The mission operations system is the integrated system of people, procedures, hardware, and software that must cooperate to accomplish these tasks.

Extracting and Processing/Surface Operations. For an automated space mining project, this is essential a sub-set of Mission Operations that focuses on the management of the platform during the period that the orbiter and landers are conducting operations in orbit around and on the surface of the target asteroid.

Marketing and Sales. This set of activities encompasses the development and execution of marketing and sales plans for the products and services to be delivered by means of the platform.

7.2. Economics of NEO Resource Utilization

Much of the recent space resources literature has focused at least in part on economic considerations, but as Sonter has noted,[86] there are still a number of economic issues that have not been rigorously addressed and a general lack of concepts that provide rapid payback. For example, Cutler and Hughes[87] have identified low initial capital investment and quick payback as the prime requirements for economic feasibility of space mining. They identified propellants and metal plate delivered to low Earth orbit (LEO) as the best products. Cutler and Hughes also identified the design and development of mining processes as the biggest research and development requirements. Cordell and Steinbronn[88] have argued that keeping initial costs down is vital. Several authors have noted that *time-cost-of-money* puts an upper limit on the allowable project cycle time, and that time from capital commitment to initial income from product sales is critical. Meinel and Parks[89] have suggested that it is necessary to achieve an internal rate of return (IRR) in excess of 30 percent per year to offset the perceived risk.

Oxnevad observed that "[t]hrough extensive sensitivity analysis, it was... shown that launch cost was not a critical parameter."[90] However, Oxnevad was operating within the framework of traditional NASA cost structures. Given a progressive approach to research and development and manufacturing costs, launch costs become a much more significant factor.

Oxnevad also observed that traditional mass payback ratio (MPBR – related to MTPR, this is a ratio of the processed resource mass returned to the mass of the mining platform launched) "does not take into account development costs, differences in value between mass launched and mass returned, nor does it take into account the time-cost of money." Oxnevad went on to point out that rigorous economic comparisons should emphasize net present value (NPV) rather than MPBR. Cutler and Hughes also argue that "high MPBR is not particularly important. Low initial capital **is** important.... Optimizing selected physical parameters such as Δ-v or Isp does."

Sonter attempts in his work to provide robust methods for comparison of different asteroid mining concepts and for choosing between various trajectory, mission, and engineering alternatives. He correctively points out that new tools are needed to help maximize project economic feasibility. He observes that we need a generic method of comparing and ranking, realistic project alternatives, including the following:

- targets asteroids/comets
- asteroid products (e.g., volatiles, metals, precious metals, semiconductors)
- mission types
- propulsion methods
- power sources
- mining, extraction, and processing methods
- guidance, navigation, and control for the outbound and return trips
- human presence vs. autonomous control of mining and processing activities
- scaling of the project

Arguing that expectation net present value (ENPV) is the appropriate measure, taking into account the probabilities of complete success, partial success, and failure scenarios, he attempts to integrate a number of the other variables into a comprehensive formula for comparing different mission concepts.

Sonter takes a valuable step towards creating a rigorous economic foundation for mission analysis. While building models that integrate orbital mechanics to help accurately forecast costs and returns and drive non-obvious insights is critical, it is not possible to integrate the entire business into a single equation. A broader perspective suggests that some of the choices that Sonter's analysis is supposed to drive are obvious, while many other considerations are not effectively accounted for. What is really needed is a specific detailed financial model of a complete mission that takes into account our current understanding of asteroid geology and the asteroid environment as well as new technologies and best practices for low-cost space missions.

In a nutshell, the capital and operating costs for asteroid mining depend on the price of equipment, space launch and operations. The need to develop a robust automated robotic mining system is likely to cause capital costs to dominate operating costs. A typical asteroid mining mission would launch the mining equipment at the first orbital phasing opportunity and expect delivery of materials at the next, 2 to 5 years later. Perceived high-technical-risk projects will need to meet very high internal rate of return (IRR) criteria, e.g., well in excess of 30 per cent per annum, to compete successfully for the required funding.

7.3. Terrestrial Mining Benchmarks

When evaluating the economic attractiveness of a space-based platinum venture, one needs to be able to achieve production costs that are competitive with (or lower than) the most efficient terrestrial producers, or the near-term, standalone business case won't fly. Even given current platinum prices (as high as they are), the cost of producing asteroidal PGMs and returning them to Earth for sale still needs to be competitive with terrestrial producers. For example, at Mimosa in Zimbabwe, which is believed to be one of the lowest-cost primary producers in the industry, costs per PGM ounce are in the region of $161/oz., and net of by-products, this drops to approximately $57/oz.[91] If one works backwards from desired production quantities and target production costs, it is possible to arrive at a set of costs and engineering requirements for an economically viable space-based PGM production operation. Whether it is possible to meet these cost requirements will depend on the actual cost and performance of the specific technical solutions chosen and, more importantly, on the details of a target asteroid's geology and environment.

Terrestrial platinum production costs will almost certainly continue to rise. As noted above (see, Section 5.3), terrestrial platinum mining is a complex, capital-intensive process. Exploration costs may run into the tens of millions of dollars over several years, and the capital costs of building a major new mine may be anywhere from $200 million to $1 billion. Compounding costs is the fact that South African mines are increasingly forced to push shafts deeper and deeper to reach high-grade ore. The ever-increasing depth of some platinum mines and the rising development costs associated with deeper operations are raising concerns in the market. Besides grades and location, the issue of increasing resource depth is becoming one of the most important factors scrutinized by investors when they consider the viability of new platinum mines or expansion projects. Deep-level mines are not only more expensive to develop, but they are also more expensive to operate, especially because of higher ventilation and cooling costs. The capital budget for Impala Platinum's new 1,800-meter-deep shaft at Leeuwkop, for example, is estimated at more than $300 million.[92]

7.4. Investment Calculations from the Literature

Little work has been done on investment requirements and the economics of developing and launching a mining operation. What analysis has been done tends to assume the traditional development processes used by government space programs to project huge development costs and very long payback periods. Estimates of the capital costs for asteroid mining equipment have used custom aerospace industry cost models originally developed for lunar mining equipment.[93] For example, Blair[94] notes that a simple calculation using the Advanced Missions Cost Model[95] developed to estimate costs for human planetary exploration missions yields an estimated cost of between $500 million and $1 billion to construct a two-ton prototype spacecraft. He goes on to note that determination of reliability and equipment service lifetimes will require engineering studies and full-scale equipment testing in a relevant environment, contributing significantly to the cost.

Gertsch and Gertsch[96] proposed a project equivalent in scale to the Anglo-French Channel Tunnel. They estimated that the project would cost at least $5 billion and requiring up to 12 years to complete. The study assumed that the asteroid mined would be made up of 150 parts per million of PGMs, a concentration thought to occur in about one in 10 platinum-bearing asteroids. Finding a suitable asteroid and mounting a mission would consume up to four years of the project, the Gertsches reasoned. On arrival, miners would need to sift through 500 million metric tons of material in order to extract enough platinum-some 68 thousand metric tons, at an assumed price of about $13 per gram-to generate a return of 100 percent on the project. However, even a 100 percent return rate would not attract the needed billions in risk capital, given the 12-year timetable and the high probability of failure, the Gertsches concluded.

As noted earlier, Sonter[97] creates an integrated model for comparing the economic viability of different types of missions, but he does not produce an estimate of the potential investment levels required to execute a successful mining operation. Wingo[98] has created an investment model for retrieving hypothesized asteroidal platinum from the Moon that would optimistically require investment of $15 billion over a decade before it would see the recovery of the first gram of platinum.

7.5. Traditional Space Mission Analogs

Development costs for innovative space science missions may also provide some additional insights into the potential cost of a robotic asteroid mining mission (Figure 22).

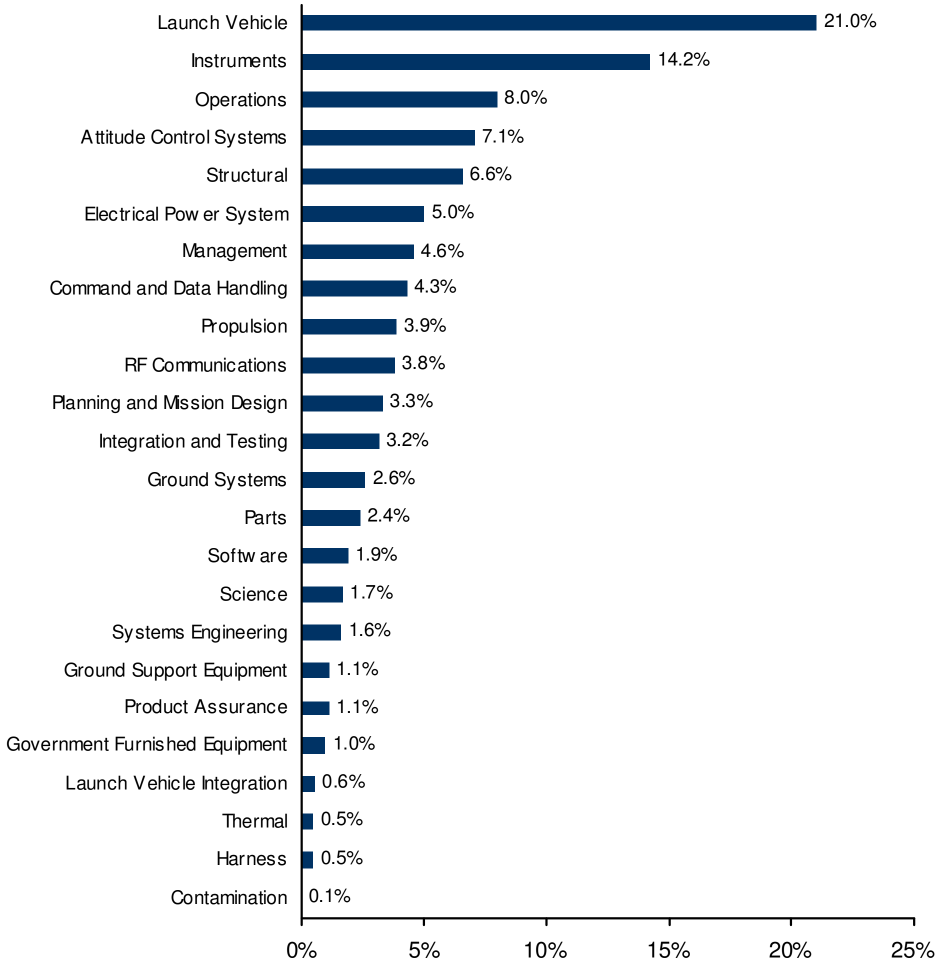
Figure 22. Costs for Selected Space Missions

Clementine	$61.9 m
NEAR	$95.5 m
Mars Pathfinder	$165.3 m
Deep Space 1	$81.9 m
Mars Global Surveyor	$109.3 m
Lunar Prospector	$63.0 m
NEAP	$50.0 m

While none of these missions is as large or complex as the proposed NEO Miner mission, each offers significant insights into potential costs for such a mission. These particular missions either used or were projected to use innovative approaches and technologies that significantly reduced costs from those of traditional missions. The development processes and the overall costs of these missions suggest some reasonable targets for the NEO Miner project.

Typically, cost estimates for a mission incorporate the total cost of the construction of the craft and its operation. Total Mission Cost is usually defined as the accumulated cost of a mission from inception (the point at which a proposal has matured into a defined new start) to completion (the predicted end of scheduled operations and data analysis). It includes in-house personnel costs and all costs associated with design, development, integration, test, launch, mission operations, and data review and archival. A breakdown of the total mission cost for a hypothetical $145-million space science mission derived from analysis of several of the missions in Figure 22 is illustrated in Figure 23.

Figure 23. Total Mission Cost Breakdown for $145-Million Mission



Source: Adapted from Liam Sarsfield, The Cosmos on a Shoestring: Small Spacecraft for Space and Earth Science, Rand Corporation Document Number MR-864-OSTP (1998).

The traditional figure of merit for spacecraft cost comparison is cost per kilogram, calculated by dividing the total mission cost by the dry mass of the spacecraft. Smaller craft generally have a higher cost per kilogram than larger spacecraft. Sarsfield suggests based on a study of small missions undertaken during the 1990s that a cost per kilogram figure of $50,000 to $75,000 might be a good target for a state-of-the-art program at that time.[99] Interestingly, design engineering is the largest element in the overall cost of building space systems. Typically, 60 percent of the budget for building a spacecraft is expended prior to fabrication.[100]

7.6. NEO Miner Cost Estimates

High-level calculations suggest that completion of the initial NEO Miner mission will require an investment of $100 to $150 million (dependent on launch costs) over five years. Initial investment is relatively small, with the most significant investment required to build and launch the actual mining platform after the completion of design and testing phases. The ability to carefully stage a modular development process with multiple opportunities to make critical decisions will significantly mitigate many risks. Initial financial requirements are modest, limited to the need to support a small, dedicated development team and software to complete rigorous, detailed design and analysis.

8. Conclusion and Next Steps

8.1. Conclusion

We are close to the point where NEO mining is technically and economically feasible. This paper represents an attempt to bring together many diverse insights into the capabilities required to build a technically and financially successful NEO mining capability. It is a work in progress. Much work remains to be done, but it is hoped that the ideas in this paper can spark additional insights and serve as a catalyst for future work in this important area of space development. Reader feedback is encouraged.

8.2. Next Steps

Based on work to date, several next steps are evident.

Community. The most critical step in taking the ideas in this paper from concepts to reality is to bring together a global community of experts and enthusiasts with an interest and willingness to contribute. This paper is an attempt to "open the code," to attempt to describe the state-of-the art in thinking about NEO mining and bring it together into a mission proposal in order to invite discussion and input. There is a saying in the open source software community that "given enough eyeballs, all bugs are shallow." The hope here is that given enough eyeballs, many of the challenges to NEO mining can be solved.

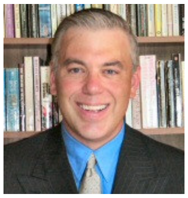
Software Tools. Another key starting point for moving forward is the development of robust, open source software tools for NEO mission analysis and design as well as for space system and spacecraft development. Computer modeling can provide rapid testing and comparison of options. It can enable the optimization of missions and the optimization of processes. This area is essential to the future of space resource utilization.

NEO Science. More comprehensive and detailed analysis of asteroid spectra and other data is also needed. This should include an accelerated program to perform the physical observations needed to characterize the NEO population, including photometry, radiometry, spectroscopy, radar, and so forth. Ostro has demonstrated the great value of radar studies using the Arecibo and Goldstone radar observatories,[101] but only a limited number of NEOs have been characterized using this approach.

Hardware and Operations. The design of a plant for mining and processing asteroidal material is a novel challenge; however, as we have seen, some concrete steps have been taken towards developing the components to such a platform. More work must be done, and to move this forward development is needed in process simulation. This is an area with obvious spin-off potential. Improved simulation requires improved models of mineralogy and better thermodynamics data. Once developed for NEO mining, the rest of the world will benefit from it as well. Other areas requiring study include anchoring into regolith on a body which has milli-g gravity; collection and handling material in milli-g gravity; power requirements; and work on system integration requirements and minimum mass for required throughput.

NEO Models and Simulants. No one appears to have yet developed simulants of asteroidal regolith that can be used for testing extraction and mining technologies. Development of these laboratory simulants for testing of extraction processes will be necessary. Lunar simulants have been developed[102] and successfully employed in processing experiments.[103] Sonter et al. have also reportedly developed cometary simulants for testing processes for mining volatiles from comets.[104] A realistic near-term goal would be to use data obtained from NEAR-Shoemaker, meteorite studies, and other research to create computer models and basic asteroidal regolith simulants for research. These materials would be able to mimic the response of chondrite ore under a range of processing conditions. In addition, we can do complex computer modeling of surface conditions, including gravitational, rotational and surface temperatures. Models can also be used to help determine regolith particle size and composition.

About the Author



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Notes

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[1] Much of the literature of space natural resources development discusses the role that these resources may play in overcoming the closed system perspective that informs much of our perspective on the limits of terrestrial resources. See, e.g., J. Peter Vajk, Doomsday Has Been Cancelled, Peace Press (1978); Dennis Wingo, Moonrush: Improving Life on Earth with the Moon's Resources, Apogee Books (2004).

[2] Indeed, many scientists believe that we already use asteroid resources based on the belief that major nickel and platinum deposits at Sudbury in Canada and in South Africa are the results of ancient asteroid impacts.

[3] E.g., John S. Lewis, "Logistical Implications of Water Extraction from Near-Earth Asteroids, Space Manufacturing 9, Space Studies Institute (September 1992); Anthony Zuppero, "Discovery of Abundant Accessible Hydrocarbons Nearly Everywhere in the Solar System", in Space 96, The Proceedings of the 5th International Conference on Engineering, Construction, and Operations in Space, American Society of Civil Engineers (ASCE) (1996).

[4] For a good discussion of the resource base of the solar system, see William K. Hartmann, "The Resource Base in Our Solar System." In Ben R. Finney and Eric M. Jones, Interstellar MIgration and the Human Experience, University of California Press (1985), pp 26-41.

[5] According to R.P. Binzel, et al., only about 50 short-period comets are currently known to satisfy the NEO definition of having a perihelion distance of ≤ 1.3 AU. See, Richard P. Binzel, et al., "Physical Properties of Near-Earth Objects." In William F. Bottke, et al. (eds.) Asteroids III, University of Arizona Press (2002), pp 256.

[6] P.R. Weissman and H. Campins, "Short-Period Comets." In J.S. Lewis, M.S. Matthews and M. Guerrieri, eds., Resources of Near-Earth Space, University of Arizona Press (1993).

[7] D. Morrison, et al., "Dealing with the Impact Hazard." In William F. Bottke, et al. (eds.) Asteroids III, University of Arizona Press (2002), pp. 739-56.

[8] D. Morrison, et al., "Dealing with the Impact Hazard." In William F. Bottke, et al. (eds.) Asteroids III, University of Arizona Press (2002), pp. 739-56.

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[27] NASA's Deep Impact mission, scheduled to release an impactor that collides with the Comet Tempel 1 on July 4, 2005, is expected to greatly enhance our understanding of comet structure and composition. According to NASA, the Deep Impact mission is designed to help answer several key questions:
What are some basic properties of the nucleus, for example: what does its landscape look like, how dense is it, how strongly is it held together and how massive is it? How has the comet changed during its lifetime? What kinds of ice remain unchanged from the comet's early days? Can the heat of the sun finally drive all the ice out of a comet so that it becomes extinct or will it only go to sleep perhaps to wake again? Do smaller comets collide and form larger comets? Are there impact craters on comets like there are on moons and asteroids? Can the course of a comet be altered to reduce the effect of, or avoid, a collision with Earth?

[28] Anthony C. Zuppero and Michael G. Jacox, Near Earth Object Fuels (neo-fuels): Discovery, Prospecting and Use, IAA-92-0159, World Space Conference Institute for Astronautics and Aeronautics, Washington, DC (Aug. 30 – Sept. 2, 1992).

[29] See, e.g., David Smitherman and John Fikes, "Space Resource Requirements for Future Propellant Depots," Space Resources Utilization Roundtable III, Colorado School of Mines (2001).

[30] Solar thermal steam rocket citation; Anthony C. Zuppero and Michael G. Jacox, Near Earth Object Fuels (neo-fuels): Discovery, Prospecting and Use, IAA-92-0159, World Space Conference Institute for Astronautics and Aeronautics, Washington, DC (Aug. 30 – Sept. 2, 1992).

[31] These factors are adapted from M.J. Sonter, "Near Earth Objects as Resources for Space Industrialization" (2001), where he argues that the "Economic Imperative" requires a space venture to minimize CAPEX, minimize payback time, and maximize NPV. While he is absolutely correct, the practical implications are that you must focus on products for which there is an existing market.

[32] See, e.g., Futron Corporation, Space Tourism Market Study (September 2004); Patrick Collins, Meeting the Needs of the New Millennium: Passenger Space Travel and World Economic Growth, IAF Congress (2001).

[33] See, e.g., J.F. Santarius, "Lunar He3 and Fusion Power," (September 2004), presented at IEEE Rock River Valley Section, Rockford, IL (September 28, 2004); Harrison H. Schmitt, "Business Approach To Lunar Base Activation," (December 2002), accepted by the Space Technology and Applications International Forum (STAIF-2003), Albuquerque, NM (February 2-3, 2003).

[34] E.g., Orbital Recovery Corporation; see, Donald M. Waltz, On-Orbit Servicing of Space Systems, Krieger Publishing Company (1993) for detailed discussion of orbital repair and servicing concepts.

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[37] One of the events that led this author to begin exploring the feasibility and economics of NEO resource utilization in depth was discussing observing the experience some of my consulting colleagues had trying to salvage a very generic Internet hosting business in which investors had already sunk approximately $400 million. Vast sums of money were invested in business plans that, in retrospect, had little or no chance in becoming sustainable businesses.

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[44] Dennis Wingo bases his whole argument for investing in the infrastructure to mine hypothesized asteroidal PGMs in impact craters on the Moon and return them to Earth on the argument that a new source of PGMs will be required to meet the demands of a full shift to a hydrogen economy. See, Dennis Wingo, Moonrush: Improving Life on Earth with the Moon's Resources, Apogee Books (2004).
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[57] "Mars Rover Is Landing again — In Toy Stores," MSNBC, http://www.msnbc.msn.com/id/3995587/ (January 18, 2004).
[58] See, e.g., John S. Lewis, "Logistical Implications of Water Extraction from Near-Earth Asteroids, Space Manufacturing 9, Space Studies Institute, September 1992; Anthony Zuppero, "Discovery of Abundant Accessible Hydrocarbons Nearly Everywhere in the Solar System", in Space 96, The Proceedings of the 5th International Conference on Engineering, Construction, and Operations in Space, American Society of Civil Engineers (ASCE) (1996).
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