Near-Earth Asteroid Mining

Shane D. Ross
Control and Dynamical Systems
Caltech 107-81, Pasadena, CA 91125
shane@cds.caltech.edu

December 14, 2001
Space Industry Report

Abstract

The near-Earth asteroids are likely targets for resources to support space industrialization, as they appear to be the least expensive source of certain needed raw materials. Furthermore, exploitation of asteroids for precious metals and semiconducting elements is a possible environmentally friendly remedy for impending terrestrial shortages of these resources.

This paper discusses the resources available from NEAs, as well as the technical engineering aspects of possible mining project designs, including a survey of mission plans, mining and extraction technqiues that may be used.

The concept of Net Present Value is briefly introduced as the appropriate measure to determine the technical economic feasibility of a hypothetical NEA mining operation, just as it is the appropriate measure for the feasibility of a proposed terrestrial mining venture.

Contents

List of Tables

List of Figures

1 Introduction

Asteroid mining is a concept that involves the extraction of useful materials from asteroids. Due to their accessibility, near-Earth asteroids (those asteroids that pass near the Earth, also known as NEAs) are a particularly accessible subset of the asteroids that provide potentially attractive targets for resources to support space industrialization.

Many materials could be extracted and processed from NEAs which are useful for propulsion, construction life support, agriculture, metallurgy, semiconductors, and precious and strategic metals (see Table 1). Volatiles such as hydrogen and methane could be used to produce rocket propellant to transport spacecraft between space habitats, Earth, the Moon, the asteroids, and beyond. Rare-earth metals could be used to manufacture structural materials as well as solar photovoltaic arrays which could be used to power space or lunar habitats. These solar cells could also be used in a constellation of solar power satellites in orbit around the Earth in order to provide electrical power for its inhabitants. Precious metals such as platinum, platinum-group metals (PGMs), and gold are also available.

Table 1: **Useful Products Obtainable from NEAs.** The volatiles and metals found in asteroids are categorized by their primary use. The molecules and elements shown here are based on the spectral properties of the entire asteroid population and chemical analysis of meteorites on Earth, which are believed to come from asteroids.

Volatiles	
Primary Use	**Molecules**
Life Support	H_2O, N_2, O_2
Propellant	H_2, O_2, CH_4, CH_3OH
Agriculture	CO_2, NH_4OH, NH_3
Oxidizer	H_2O_2
Refrigerant	SO_2
Metallurgy	CO, H_2S, $Ni(CO)_4$, $Fe(CO)_5$, H_2SO_4, SO_3
Metals and Semiconductors	
Primary Use	**Element**
Construction	Fe, Ni
Precious Metals	Au, Pt, Pd, Os, Ir, Rh, Ru, Re, Ge
Semiconductors	Si, Al, P, Ga, Ge, Cd, Cu, As, Se, In, Sb, Te

1.1 Space Industrialization

The industrialization and settlement of space is likely to be brought about primarily by increasing commercial activities in space, worth several billion dollars per year, including the following existing activities: telecommunications, direct broadcast television, navigation (e.g., the Global Positioning System), remote sensing, and metereological services. Low Earth orbit (LEO) satellite constellations will roughly double the annual income of these services over the next decade (Sonter [1997]).

1.2 Future Market for Raw Materials

1.2.1 Space-Based Market

Other space-based commerce may come online within the next few decades, including manufacturing, solar power stations, and space tourism. There is interest in space-based production of high value pharmaceuticals, semiconductors, ultra-pure crystals for many applications, and generally anything requiring large-scale material purity. The concept of satellite solar power stations (SSPS) is again receiving active consideration: the Japanese have considered an equatorial orbit SSPS pilot plant, orbiting at 1100 km altitude, of mass 200 tonnes[1] (Nagatomo, M. [1996]). Japan's National Space Development Agency, which hopes to launch an experimental version of an SSPS between 2005 and 2007, has asked two teams of private companies to submit design proposals by the end of January 2002.[2]

The feasibility of space tourism is also being promoted. Market research in the United States, Japan, Canada and Germany has shown that as many as 80% of people younger than 40 would be interested in commercial space travel. A majority would be willing to pay up to three months' salary for the privilege. Ten percent would pay a year's salary.[3] It is estimated that at a launch cost of $200/kg the space tourism industry will grow rapidly to several billion dollars per year (Collins et al. [1994]). Hotels in orbit will be needed to cater for 10,000 person accomodations after some years. The Japanese Shimizu Corp., an engineering and construction firm, has developed a plan for such an orbiting hotel, of mass 6000 tonnes. They have pledged to have their 64-room hotel aloft by 2020, with a lunar unit to follow.[3]

As a result of these and other activities, we can expect a future market for mass in LEO, i.e., metals for construction, volatiles to make propellants for stationkeeping and transportation, and unprocessed mass for shielding against cosmic radiation. The size and rate of this future in-orbit market for materials could exceed 1000 tonnes per year by 2010, growing exponentially to tens of thousands of tonnes per year if any large scale activity develops rapidly (Sonter [1997]).

1.2.2 Earth-Based Market

Many terrestrial resources, such as precious metals and fossil fuels, are running out. As new terrestrial sources are sought, materials are obtained at increasing economic and environmental cost. Society pays for this depletion of resources in the form of higher prices for manufactured goods, would-be technologies that are not developed for lack of raw materials, global and regional conflicts spurred by competition for remaining resources, and environmental damage caused by development of poorer and more problematic deposits.

Utilization of asteroid resources may provide a partial solution to the problem, as they hold the potential for becoming the main sources of some metals and other materials. Precious metals and semiconducting elements in iron meteorites, which form the metallic cores of asteroids, are found in relatively large concentrations compared to Earth sources. In such sources, it may be possible to extract up to 187 parts per million (ppm) of precious metals, which includes Au, the Pt-group metals (Pt, Ru, Rh, Pd, Os, and It), Re, and Ge. More than 1000 ppm of other metals, semiconductors, and nonmetals may may one day be extracted and imported by Earth from asteroids, such as Ag, In, Co, Ga, and As.

---

[1] A tonne is a metric ton (10^3 kg).

[2] Associate Press, 29 October 2001, http://www.space.com./businesstechnology/technology/nasda_solar_sats_011029.html

[3] *Houston Chronicle*, 28 October 2001, http://www.chron.com/cs/CDA/story.hts/metropolitan/1107492

1.2.3 Estimated Market Value.

Kargel [1997] estimated that one metallic asteroid of modest size (1 km) and fair enrichment in platinum-group metals would contain twice the tonnage of PGMs already harvested on Earth combined with economically viable PGM resources still in the ground. At recent prices, this asteroid's iron, nickel, PGMs, and other metals would have a value exceeding that of the world's proven economic reserves of nonmetallic and metallic mineral resources. The availability of asteroid metals would lower market prices. Even then, the value of the asteroid-derived materials would be enormous.

The mining scenario Kargel considered is one involving coproduction of precious metals (for Earth markets) and semiconductors marketed to a future space photovoltaics industry (e.g., for production of solar power cells). He assumed the asteroid mined to be a 1 km metallic asteroid in the 90th percentile of iridium richness, because this type is rich in semiconductors. As it turns out, the semiconductors are where most of the money is if there is a large-scale space solar power industry (see Table 2).

The precious metals would be sold in Earth markets, and would be insensitive to launch costs. However, Kargel assumed that asteroidal semiconductors placed into LEO would acquire a value p, approximated by $p = p\prime + C_{orbit}$, where $p\prime$ is the cost of these materials purchased from terrestrial sources, and C_{orbit} is the launch cost to LEO per kg. There, they would be made into photovoltaics, as it is advantageuous to do the manufacturing in space rather than launch prefabricated modules from Earth (owing to launch cost considerations). Currently, C_{orbit} ∼$20,000/kg on most systems. Kargel assumed that efficient high-volume launch systems would be developed in the near future, lowering the launch cost to $3,000/kg, i.e., a reduction that would seem sufficient to make commercial space solar power economical.

1.2.4 Capital Required

Space mining could entail capitalization of a $100 billion or more (Kargel [1996]). Historically, private ventures for large and risky engineering projects have been capitalized at comparable levels: $20 billion was spent on the Alaska Pipeline, and an estimated $55 billion will be spent for Indonesian oil and gas exploration.

1.2.5 Current Projects

NEAP: Near-Earth Asteroid Prospector Mission. SpaceDev, a public company based in southern California, has a plan to develop a mission known as the Near Earth Asteroid Prospector (NEAP).[4] This low-cost mission (less than $50 million) would involve a 220 kg microsatellite launched as a secondary payload on a European Ariane 5 expendable launch vehicle. It will land a payload on the surface of an asteroid and will be a demonstration of the potential for commercial mining of asteroids. The mission could be the first deep-space mission defined and executed by a non-governmental entity, and SpaceDev could be the first private company to go up into space, collect space data and sell it. When the mission was first conceived in early 1997, only about 300 NEA targets had been discovered. SpaceDev tentatively selected 4660 Nereus, possibly a carbonaceous near-earth asteroid, as its NEAP mission target. The number of known NEAs is now over 1,500 providing many more options than previously available (see Figure 2.1). Currently, SpaceDev intends to launch NEAP in 2002, contigent on full financing which is not assured at the time of this writing.

---

[4] SpaceDev, http://www.spacedev.com

Table 2: **Market Value of Semiconductors and Precious Metals for an Example Metallic Asteroid.** World prices are from 1994. The asteroid is assumed to be a 1 km metallic asteroid (90th percentile in iridium richness). The ore is assumed to be mined at a rate of 10^6 m^3/yr. At this rate, the ore would last over 500 years before depletion. (Taken from Kargel [1997].)

Element	Price (US$/kg)	Concentration (ppm)	Mine Capacity (tonnes/yr)	Tonnes sold per year	Sales ($M/yr)
Semiconductors[5]					
Phosphorous (P)	0.08	1300	10,100	722	2,167
Gallium (Ga)	300.00	60	468	468	1,544
Germanium (Ge)	745.00	210	1,640	1,640	6,145
Arsenic (As)	0.94	3.7	28	28	85
Selenium (Se)	10.47	36	281	281	846
Indium (In)	160.00	0.46	4	4	11
Antimony (Sb)	3.92	0.047	0.4	0	0
Tellurium (Te)	57.32	0.45	4	0	0
Total for Semiconductors:				3,143	10,798
Precious Metals					
Ruthenium (Ru)	365.00	13.0	101	101	8
Rhodium (Rh)	23,052.00	4.8	38	38	287
Palladium (Pd)	4,565.00	1.3	10	10	43
Silver (Ag)	160.00	0.46	4	4	1
Rhenium (Re)	1,557.00	3.7	28	28	32
Osmium (Os)	12,860.00	9.0	70	70	307
Iridium (Ir)	965.00	33.0	257	257	20
Platinum (Pt)	12,394.00	35.0	273	273	1,705
Gold (Au)	12,346.00	0.5	4	4	49
Total for Precious Metals:				583	2,452
Grand Total:				3,726	13,250

2 Assessment of Near-Asteroid Resources

2.1 Non-Terrestrial Resources

Astronomical work over the last fifteen years has increased the number of known NEAs from about 30 to about 1,500. See Figure 2.1. The discovery rate is now above 200 per year. Some 500 of the known NEAs are estimated to be of diameter 1 km or more. Asteroid geology has also advanced dramatically in the last decade, drawing on spectroscopic and dynamical studies of asteroids and comets, and meteorite studies. Reasonable correlations can now be made between spectral / photometric asteroid types and inferred surface mineralogy. It is now believed that as many as 50% of the NEAs may be "volatiles bearing," containing clays, hydrated salts, and hydrocarbons. It has also become clear that the NEAs are much more rich in desired raw materials than the Moon.

---

[5] Semiconductors are assumed to be sold at a price $p = p\prime + C_{orbit}$, where $p\prime$ is the price shown and C_{orbit} = $3,000/kg.

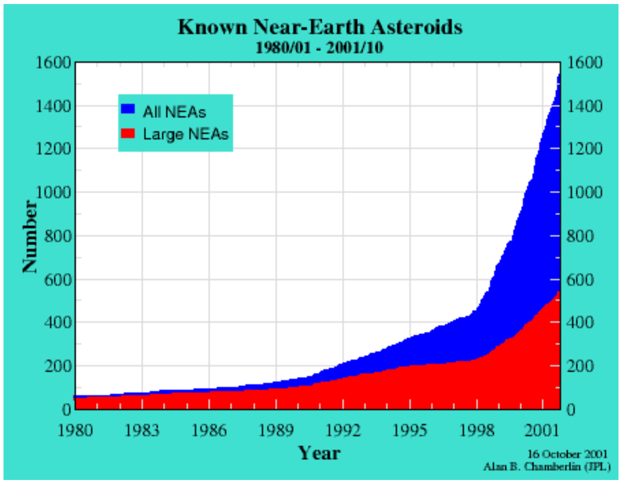

Figure 2.1: The cumulative total known near-Earth asteroids versus time (from Chamberlain (JPL/NASA) [2001]). Large NEAs are those estimated to have diameters greater than 1 km.

2.1.1 Near-Earth Asteroid Resources

The compositions of asteroids are inferred from laboratory studies of meteorites and from the spectral reflectivity studies of asteroids at ultraviolet, visible, and near-infrared wavelengths. A rough spectral taxonomy of asteroid types separates them into three categories:

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

The NEAs are very diverse in their spectral properties, ranging from metallic iron (M-type) to stony (S-type) to very black carbonaceous (C-type) material. About half of the kilometer-sized NEA population and therefore about half of the mass of the NEAs, is believed to be carbonaceous, and thus carbon- and water-rich (Lewis [1997]). 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-carbonaceuous asteroids contain the following: about 20% metallic iron-nickel alloy; about 6% of the ferrous sulphide mineral troilite, and large amounts of olivine, pyroxene, and plagioclase feldspar; trace amounts of rare and valuable metals (especially platinum group metals) and non-metals (such as arsenic, selenium, germanium, phosphorous, carbon, sulphur, etc.). The minerological, chemical and physical properties of four different asteroids based on four different meteorites are shown in Table 3.

The 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 cumbly, 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.

Table 3: **Minerological, Chemical and Physical Properties of Asteroids.** We show four different asteroids based on four different meteorites. Note that meteorites vary dramatically in composition, and below we show only sample meteorites from within just four categories (from O'Leary et al. [1979] and Apollo 11 lunar soil sample data).

	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%
	H_2O	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%
	SiO_2	33.8%	28%	38%	—	42.5%
	MgO	23.8%	20%	24%	—	8.2%
	Al_2O_3	2.4%	2.1%	2.1%	—	13.8%
	Na_2O	0.55%	0.3%	0.9%	—	0.44%
	K_2O	0.04%	0.04%	0.1%	—	0.15%
	P_2O_5	0.28%	0.23%	0.28%	—	0.12%
	CaO	—	—	—	—	12.1%
	TiO_2	—	—	—	—	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

Carbonaceous chondrites are subdivided into five categories:

- *C1 carbonaceous chondrites* average about 10% water in a clay mineral matrix and as water of hydration (often in magnesium salts, 5% to 15%), 2% to 5% carbon in the form of graphite, hydrocarbons and organic compounds, several percent sulfur in elemental, iron sulfide and water soluble sulfate forms, some nitrogen and other volatiles, and 5% to 15% magnetite.
- *C2 carbonaceous chondrites* have very little magnetite, a little less water, carbon, and sulfur, and about 10% soluble sodium and magnesium salts, all in a mineral assemblage.
- *C3, C4 and C5 carbonaceous chondrites* are not really "carbonaceous" as their name implies but instead are very poor in water, carbon and other volatiles, but have other semblances to C1 and C2 carbonaceous chondrites.

2.1.2 Compare With the Moon

Many assume the Moon to be the obvious source of resources in space, but it is instructive to compare the richness of the resources available in meteorites (and by inference in the NEA population) with that of the Moon. Typical free metal concentrations in stony meteorites are about 20%, compared to a few hundred ppm in the lunar regolith. Iron meteorites, or metallic M-type asteroids, are even more metal-rich; about 99%

---

[6] This estimate is based on solar wind deposition of hydrogen (see text)

metal. C-type asteroids and carbonaceous meteorites typically have 5% to 20% water. The lunar surface, by contrast, has no native water. Solar wind implantation of hydrogen on the lunar surface offers up to about 50 ppm hydrogen, which, if fully released and fully converted into water, would optimistically give the lunar surface about 0.045% water. Overall, the lunar surface is volatile-poor and metal-poor, similar in composition to the slag discarded in metallurgical processing on Earth (Lewis [1997]).

3 Trajectory Planning: Rendezvous and Return

In this section, we will consider the propulsion necessary to retrieve material from an asteroid.

3.1 Accessibility and Astrodynamical Considerations

As mentioned earlier, according to Chamberlain [2001], there are now over 1,500 identified NEAs, defined as objects whose orbits have a perihelion less than or equal to 1.3 AU (see Figure 2.1).[7] Lewis [1993] estimates that the total population of NEAs with diameters over 1 km is at least 1000, and those with diameters greater than 100 m may number at least 100,000.

In space, the parameter which measures the difficulty of delivering mass from one orbit to another is not distance, but the required velocity change, delta-v (also denoted Δv), needed to perform this transfer. A comparison of velocity increments necessary for various tranfers is shown in Table 4. Note that it is much easier to go from LEO to nearly anywhere in the inner solar system than it is to into LEO from Earth's surface.

Table 4: **Delta-V Requirements for Various Transfers.** Data taken from Lewis [1991] and Sonter [1997].

Transfer	**Delta-V (km/s)**
Earth surface to LEO	8.5
Earth surface to escape velocity	11.2
Earth surface to GEO	11.8
LEO to escape velocity	3.2
LEO to Mars or Venus transfer orbit	3.7
LEO to GEO	3.5
LEO to HEEO[8]	2.5
LEO to Moon landing	6.3
LEO to Near Earth Asteroid[9]	4.0
Lunar surface to LEO (aerobraking)	2.4
NEA to Earth transfer orbit	1.0
Phobos / Deimos[10] to LEO	8.0

---

[7] Of these, about 350 are classified as PHAs (Potentially Hazardous Asteroids), meaning that their orbits come within 0.05 AU (7.5 million km) of the Earth's orbit.

[8] Highly eccentric Earth orbit

[9] 4.0 km/s is the minimum for known NEAs; 200 known NEAs are under 6.5 km/s.

[10] Phobos and Deimos are the asteroid-like moons of Mars.

Lewis [1993] also estimates that 10% of all NEAs are more accessible in terms of delta-v than the Moon, and are very much easier to return to Earth from than the Moon. Using the Shoemaker-Helin formulae for estimating the probable likely minimum delta-v for Hohmann transfers to and from these bodies (Helin and Shoemaker [1978]), Sonter [2001] estimated that about 90 known NEAs (6% of the known total) are more accessible than the Moon, i.e., have a minimum outbound delta-v from LEO for rendezvous of less than 6 km/s. About 200 have "global minimum" outbound delta-v's from LEO under about 6.5 km/s. A few have outbound delta-v's under 4.5 km/s, with one object (1991 VG) slightly under 4.0 km/s.[11] Similarly, a few have delta-v's for return departure on the order of 1 km/s.

Additional Astrodynamical Considerations. There are a few astrodynamical considerations to keep in mind regarding NEA rendezvous and retrieval. The launch windows for the "global minimum" opportunities computed from the Shoemaker-Helin formulae are infrequent, but somewhat higher energy local minima occur more frequently for most NEAs. On the Earth-return portion of the journery, the hyperbolic velocity with respect to Earth should be kept low. High-eccentricity NEAs will likely require Hohmann transfers, and because they typically have a shorter synodic period[12] , any mission will have to have a short mining season at aphelion. Low-eccentricity NEAs can be reached by continuous (low-)thrust propulsion, and extended mining season.

3.2 Mission Plans and Trajectories

When we consider the alternative out-and-return trajectories to different NEAs, taking into account allowable stay times for resource extraction, it is found that several alternative mission trajectory types are identified. The alternatives arise because:

- targets may be in low or high eccentricity orbits;
- targets may have perihelion inside or outside earth orbit;
- the transfer from the target to the Earth may be by Hohmann ellipse (impulsive thrust) or by continuous low-thrust propulsion;
- the mining season may be short-term or extended (at least one synodic period, typically 10 years);
- if short-term mining season, it may be aphelion-centered or perihelion-centered.

In the following paragraphs, we will look at alternative mission plans to the NEAs, or more specifically, Near Earth Objects (NEOs), which includes asteroids and comets with perihelion distance q less than 1.3 AU. The vast majority of NEOs are the NEAs, which are divided into three groups based upon the orbital elements perihelion distance q, aphelion distance Q, and semi-major axis a: Atens ($a < 1.0$ AU, $Q > 0.983$ AU), Apollos ($a > 1.0$ AU, $q < 1.017$ AU), and Amors ($a > 1.0$ AU, $1.017 < q < 1.3$ AU). A fourth, and as yet very small group of asteroids are the Arjunas. An Arjuna-type asteroid is one with a nearly Earth-like

---

[11] The theoretical minimum is 3.2 km/s, the delta-v needed to go from LEO to a (Earth-escaping) heliocentric orbit. But any NEA this "accessible" would likely have had repeated close encounters with the Earth, ending in collision in a short astronomical time (Koon, Lo, Marsden, and Ross [2000]). Thus, the most accessible asteroids have probably been cleaned out by collisions with the Earth earlier in the solar system's history.

[12] The time between the least separation between the Earth and the NEA.

orbit.[13] The Near-Earth Comets (NECs) are short period comets with $q < 1.3$ AU which have an orbital period P less than 200 years. The discussion follows that of Sonter [1997].

3.2.1 Apollo-Type: Apollo or High-Eccentricity Amor Asteroids

Objects with high eccentricity, low-inclination orbits demand Hohmann transfers for both outbound and inbound trajectories, because of their relatively high delta-v requirement. Mining season is limited to a short period during aphelion; return delta-v must be achieved in a small fraction of T, the period of the transfer orbit.

This trajectory assumes rendezvous near but before aphelion for minimum Δv_{out}; a short aphelion-centered mining season, (for example, a 3 month mining stay); and a post-aphelion departure for Earth-return, with approximately 3 month thrusting, for minimum Δv_{return}.

There is a need to destroy a relatively large return (hyperbolic) arrival velocity. This criterion, i.e., the delta-v requirement to achieve Earth-capture, is in fact far more demanding than the asteroid-departure delta-v requirement. In fact, even for the lowest hyperbolic velocity cases, namely return from very low eccentricity objects with semi-major axes similar to the Earth's, the delta-v for capture is the largest part of the entire trip delta-v.

Mission duration must approximate the period T of the transfer orbit which itself must approximate an integer number of years, to enable rendezvous with earth on return, without a phasing orbit, which would extend the mission duration significantly. This is undesirable as it will negatively effect the net present value (NPV) of the project, the economic figure of merit for mining missions, to be discussed in a later section. To minimize return departure delta-v, the object's orbit should be Earth-grazing , i.e., $q \simeq 1.0$ AU.

3.2.2 Aten-Type: High Eccnetricity Atens

This mission type assumes a Hohmann transfer to rendezvous with the target asteroid at its perihelion. A near-aphelion departure occurs after half an orbit stay time. Post-perihelion departure is ruled out, because this gives inadequate mining season duration.

An alternative mission profile is to use an aphelion arrival (requiring high delta-v's to rendezvous) and a perihelion departure for low return delta-v requirement. Whether to choose perihelion or aphelion rendezvous for these Aten-type missions needs to be determined on an individual basis, by checking Δv_{out} and Δv_{return}, and total time of mission.

3.2.3 Arjuna-Type: Arjunas and low-eccentricity Amors

The Arjunas, and some Amors, have very nearly circular orbits. Such close, low eccentricity, low inclination NEAs, may be favorable for continuous low-thrust spiral, non-Hohmann returns; a characteristic of these trajectories is the softness of the launch window for return.

Slow spiral return transfers imply a longer mining season, and longer return trip duration, and hence less demanding specifications on mining, processing, propulsion equipment, and solar power conversion systems. Note that spiral return trajectories can be designed to deliver the payload at very small v_{hyp} (hyperbolic Earth return velocity), because the spacecraft trajectory can be made tangent to the Earth's orbit. Such low v_{hyp} implies easy capture into HEEO (Highly Elliptical Earth Orbit).

---

[13] Lunar and Planetary Laboratory, Univeristy of Arizona, http://www.lpl.arizona.edu/spacewatch/nea.html

3.2.4 Short Period Comets

Perihelion rendezvous may be appropriate for mining short period comets, as discussed by Kuck [1995], because (i) solar insolation is too weak at aphelion; (ii) more importantly, aphelion rendezvous imposes financially disastrous time delays.

Dormant comets may be desirable targets because (i) drilling is assumed to achieve close to 100% recovery and capture of liberated volatiles; (ii) equipment for in-situ melting is likely to be considerably less massive than equipment for mining and processing regolith (possibly by factor of 10).

This is counter-balanced by the very much higher delta-v requirement for return, which translates into a requirement for much higher propellant usage on return transfer, and hence a larger "mining" requirement (to get mass for use as return trip propellant), and by the constraint of a very short mining season.

3.2.5 High Inclination, Low Eccentricity Targets

The overriding characteristic of these missions is the need for high thrust during passage through the nodes. Inclination change will be a major propulison demand, ($\Delta v_{inclin} \simeq 0.5 \times i$ km/s, where i is in degrees), so timing of mission phases with respect to ascending / sescending nodes is important for these cases.

3.3 Return to Earth Orbit

A major energy cost of the return mission is to decelerate the payload so as to achieve Earth-capture. There are various possibilities for reducing velocity from hyperbolic to a bound orbit upon return.

- **Propulsive braking.** Use propulsive braking using some of the Asteroid-derived propellant. This method is simplest, but may be undesirable, as it reduces the quantity of material that is available for sale.

- **Aerobraking.** Use an Earth-fabricated, LEO-fabricated, or asteroid-fabricated aerobrake made of metallic or refractory silicate. The problem is, to fabricate an aerobrake on an asteroid, by remote means, adds another level of complexity. Such a mission may require a human presence and thus increase the cost substantially.

- **Lunar assisted capture.** Use a lunar flyby to reduce, and in fact remove, the Earth hyperbolic velocity. This will naturally insert the returning craft into HEEO. Severe 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/s is achievable for a single lunar flyby (O'Leary et al. [1979). This applies to an object returning on a transfer orbit of $Q \simeq 1.25$ AU from an aphelion mining mission and an object returning on a transfer orbit of $q \simeq 0.83$ AU from a perihelion mining mission.

4 Mining, Extraction, and Production

Once rendezvous with an asteroid is achieved, the mining, extraction, and processing operations must be established. We will discuss some aspects of the mining and extraction process, as well as in-situ propellant production, following O'Leary et al. [1979] and Sonter [1997].

4.1 Anchoring to the Asteroid

In any operation, the mining machinery must first be anchored successfully to the asteroid surface or subsurface, and the released material must then be efficiently contained and recovered. Containment will be important, because the escape velocity for small asteroids may be of the order of 20 cm/s.

Mining on asteroids will, because of the low gravity, require positive anchoring of the digger, drill, pick, or cutting head, so as to generate adequate force against the regolith, rock, ice, or metal. Securing is easy with rigid, competent, strongly bonded matrices. One can set anchors, drive in pitons, glue or adhere to the surface, or clamp against opposing surfaces. But it is likely to be very difficult with low strength or unconsolidated material, such as loose asteroidal regolith or the hypothesized loose dusty covering of a dormant or extinct comet. The reaction forces created by such operations as drilling or scraping may in that case require the operation to be spread over a very wide footprint, if the regolith strength is low, and because of the milli-g gravity. This may need very wide area anchoring, over an extended footprint, including the approach of totally surrounding the target body, by wrapping it with a net or membrane.

Possibilities for securing to an asteroid are:

- tie the spacecraft down with a rope passing around the entire NEA
- drive in pitons – assues that the material is mechanically competent
- fire in harpoons or penetrators which resist extraction
- screw in large area augers or screw-plates – assumes that there is a regolith and it is loose enough and compressible enough for a screw to penetrate
- weld tie-downs into massive clasts of metal, ice, or solid silicate rock
- use large area fluked anchors
- burrow completely into the regolith (e.g., using contra-rotating screws)

4.2 Mining Methods

The mining method will depend on the material being sought. If regolith, the method will clearly be very different from that chosen if recovering solid metal; different again, if the ore is high in volatiles and ices. Loose material can be scooped, scraped, or shoveled. Friable but bound material will have to be broken or cut, or somehow disaggregated, before collection. Hard rock will require drilling, cutting, or blasting. If it is necessary to break rock, then that requires that a force be exerted against the rock surface, either by impact or by pressurization or by static loading (e.g., the impact of a pick, the pressurization of a drill hole by an explosion, or the static loading by the teeth of a roadheader or cutting discs of a tunnelborer). Classical percussion drills use the inertia (of a large machine) or pneumatic pressure (of the airleg) to resist the normal reaction of the face being bored. Down-the-hole-hammer drills react against the inertia of the drill string and indirectly its friction against the side of the hole. Tunnelborers clamp against the already-cut tunnel walls.

Mining approaches will depend on the material:

- loose regolith – scraper, etc.

- competent silicate matrix – drill and blast or cut
- silicates and ices or hydrocarbons – vaporization
- silicate and metal – cut and crush
- extensive metal – cut

More exotic approaches may include carbonyl volatilization, or electrolytic release.

Frozen volatiles may be cut or mechanically mined, or melted or vaporized for extraction. Solid metal must be cut or melted at high temperature, or reacted at a lower one, e.g., using the carbonyl vapor-metallurgical process, as proposed by Lewis and Nozette [1983] and Lewis, Jones, and Farrand [1988].

4.2.1 Surface Mining

Gertsch [1984] proposed the classical three-drum slusher/scraper for lunar regolith mining operations, because of its simplicity and low mass. However, this is probably inapplicable to asteroids, where the overriding considerations appear to be (i) very low strength regolith; (ii) essentially zero gravity; and the (iii) need for containment. This is because in milli-g it is necessary to (i) ensure the scraper or shovel is held against the surface; and (ii) ensure that collected material is effectively retained within the collecting mechanism, and does not float away. Thus, mining on low gravity bodies will require an approach that encloses the regolith being collected, e.g., by clamshell grab or an enclosed screw conveyor or an enclosed drag chain conveyor, giving positive displacement. An enclosed flail will also disaggregate and crush.

4.3 Extraction

4.3.1 Underground Extraction.

There may be good reasons to use underground mining techniques when mining on asteroids:

- it is easier to generate reaction forces for cutting, drilling, or digging (i.e., it uses standard terrestrial technology)
- the surface layer may be depleted in the desired material (e.g., volatiles may only lay at depth under a lag deposit in a dormant comet)
- it may be easier to contain the cut or released material
- the resulting volume may itself be useful, e.g., for storage, habitat, or plant

An underground mining technology should be chosen which uses minimum consumables, or none at all. It should also not require a large normal reaction force, and should have minimal impact on ground that is suspected to be weak and friable.

4.3.2 In-Situ Extraction

A particular case of underground extraction is by fluid extraction through drillholes (Kuck [1995]). This is analogous to the Frasch process for melting and extraction of liquid sulphur from deep deposits using injected steam, and solution mining using a circulating solvent, as is practiced in in-situ leach mining of uranium ore bodies, and solution mining of salt deposits.

Kuck has listed the following benefits and risks of in-situ extraction.

Benefits:

- simplicity and smaller mass of equipment
- no mining, transportation, crushing, grinding, separation, solid material handling, or tailings disposal to worry about
- the body itself provides the reaction vessel
- no power needed to crush, grind, etc.
- much less complicated.

Risks:

- loss of drilling and heat transfer fluid due to (a) blowout or (b) intersection with large voids or fissures, or (c) excess seepage into porous or loosely consolidated matrix, (d) insufficient volatiles production to replace this fluid loss
- incomplete separation of solids from return fluid
- plugging of equipment due to precipitation by sulphur or hydrocarbons
- plugging of matrix by fine solids, clays, etc.
- insufficient matrix permeability.

Kuck's process requires much less in terms of system mass than the physical mining of soil or matrix followed by a de-volatilization process, being a requirement for a light drill-rig and a fluids collection bag, plus equipment for filtration, pressurization, and reheating for the drilling / heat transfer fluid. Kuck's process suffers from several technical threats: (i) it is essential that there actually be substantial subsurface volatiles, for example as permafrost, if not as massive ice deposits; (ii) there is a risk (always present in drilling operations) of loss of circulation: loss of drilling fluid into subsurface voids; (iii) there is the risk of blinding or clogging of the drill fluid return pathway, or of the fluid recovery and conditioning system; this clogging could be by fine sediments, clays, salts, waxes, or reaction products. A greater threat is that pressurization of the mining void within the hypothesized dormant comet could conceivably cause the body to fracture catastrophically, because the subsurface mantle layer would be too weak to resist the tensile forces generated by the pressurization.

4.3.3 Regolith Devolatilization Process

The soil devolatilization process requires a more complex materials handling plant, since it demands an actual mining plant. It must be designed for an approximately five-fold higher mass throughput than that demanded of the Kuck process. This is because the recoverable water from hydrated soil minerals cannot be assumed to be greater than about 10% by mass, whereas the Kuck process target model assumes an ice component in dormant cometary matrix of not less than about 30%. The equipment will comprise a collector, soil pressurizer, grinding mill and heater, solid - vapor separator, volatiles collector bag, tailings disposal, and gas cleaner / reheater / repressurizer.

A review of the mass throughput rates of simple industrial solids handling equipment and pneumatic heater / dryer equipment suggests that a mass throughput ratio (kilograms per day per kilogram of equipment mass) of well over 200 may be achievable. If this is so, then an equipment mass of 5 tonnes could process 1000 tonnes of asteroidal regolith per day, to produce 100 tonnes of volatiles per day, giving 10,000 tonnes of product in a 3-months mining season. Note however that to this mass must be added the mass of the requisite power source, which would most simply be solar thermal or solar photovoltaic, and the mass of the separation mechanism and the return propulsion system.

4.4 In-Space Propellant Production

The mission velocity delta-v needed to reach selected low delta-v target NEAs is not much greater than that needed to place a communications satellite in geosynchronous orbit. The delta-v required to return material from these targets is very much less than that required to lift mass into orbit from the surface of the Earth, and can be imparted gradually, over several weeks, thus very substantially reducing the demands on the propulsion / power system.

If the return transfer can be accomplished using part of the retrieved non-terrestrial mass as reaction mass, such as asteroid-derived volatiles, and solar energy for the power source, or onboard nuclear power, then it becomes possible to return to Earth orbit very much more mass than the outbound-leg Earth-orbit-departure mass of the mining-processing spacecraft. This in situ propellant production then allows a high Mass Payback Ratio (mass multiplication). Mass multiplication factors above 100 are the initial aim.

5 Project Feasibility and Economic Selection Criteria

5.1 Compare Financial Feasibility of Space Mining Proposals

One simple but important fact we can learn from modern economic theory is that time-cost-of-money puts an upper limit on the allowable mining project cycle time. Additionally, the time from capital commitment to initial income from product sales is critical. 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 year, to compete successfully for the required funding (Sonter [1997]).

It has been noted in the literature (Lewis, Ramohalli, and Triffet [1990], Oxnevad [1991]) that means of comparison of mission concepts are not well developed. Robust methods for comparison of different asteroid mining concepts, and for choosing between various trajectory, mission, and engineering alternatives, are needed so as to maximize project economic feasibility.

In the analysis of Oxvenad [1991], launch cost was shown not to be a critical parameter. Oxvenad also noted that the Mass Pay Back Ratio (MPBR) “does not take into account development costs, difference in value between mass launched and mass returned, nor does it take into account the time-cost of money.” Oxvenad believed that rigorous economic comparative analyses should emphasise net present value (NPV), a concept used in terrestrial mining project planning, rather than MPBR.

In summary, there is a need for a robust general approach for comparing the financial and technical feasibility of competing space mining project proposals, and for performing realistic risk assessments. We need a generic method of comparing and ranking, realistic project alternatives, including the following:

- targets asteroids/comets
- target materials to be reclaimed (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

Many of these choices are interrelated, as selection of a particular option in one area imposes constraints in the other areas. Also, different levels of technical maturity apply to the various options. In order to carry out the comparisons of possible projects, it is necessary to find and compute the appropriate "figure of merit."

5.2 Net Present Value is the Proper Figure of Merit

As mentioned by Sonter [1997], the proper figure of merit used to assess financial feasibility of proposed projects is the Net Present Value (NPV). Specifically, the Expectation NPV (ENPV) is the appropriate measure, taking into account the probabilities $p_j, j = 1, \ldots, s$, of the all the success, partial success, and failure scenarios (where s is the total number of scenarios considered). Sonter claims that NPV is the appropriate measure for the feasibility of a proposed terrestrial mining venture, and thus should be applied toward the feasibility of a hypothetical asteroid mining venture. He thus expands the formula for NPV in terms of astrodynamic and rocket equation variables (see Sonter [1996]).

NPV calculates the present value of receipts of money to be received n years in the future, taking into account the foregone interest that the invested money could have been earning. The longer you have to wait for the income, the less present worth it has, and the more heavily discounted it must be, in the NPV calculation.

The goal is to have a project with a large positive NPV. Projects with negative NPV should not be considered. And among those with positive NPV, the ones with the largest NPVs should be seriously considered.

NPV in the comet or asteroid mining case depends on (i) the cost to launch and conduct the mission, (ii) the mass returned and what you can sell it for, and (iii) the time it takes to accomplish the mission.

Net Present Value of a Receipt R obtained in year n is:

$$\mathrm{NPV} = R(1+i)^{-n} - C$$

where i is the market interest rate paid on investments and C is the capital spent on the project.

For a robotic mining mission to an Apollo-type asteroid, with a single payload return, using a solar-thermal steam rocket, the formula for NPV can be expanded as follows, using the rocket equation and Kepler's law determining the period of an orbit (Sonter [1997]) :

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

where

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

From this equation, we can draw some conclusions. Optimizing selected physical parameters such as Δv or I_{sp} (proportional to v_e) does not in general lead to the most economical project. Other factors must be considered, such as keeping initial capital low. Also, while outbound Δv is not critical, except within the constraints of the launcher capability, return Δv must be minimized. The duration of mining season should be maximized, consistent with minimizing total mission time and maximizing mass returned. The implications for asteroidal resource projects are that missions taking longer than (say) three years will have to have very good MPBRs, in order for the NPV to be positive.

For completeness, we note that the ENPV would include a summation over the possible outcome scenarios.

$$\text{ENPV} = \sum_{j=1}^{s} p_j \text{NPV}_j$$

6 Conclusion

6.1 Summary

Near-Earth Asteroids May Provide Resources for Future Markets. Some Near-Earth Asteroids (NEAs) offer very promising targets as future ore bodies for in-space resources, for reasons of accessibility, ease of return, apparent variety of source materials, and probable ease of extraction of both metals and volatiles, both of which are likely to be in heavy demand during the development of large-scale space infrastructure.

There may be a future market for asteroid-derived material. This market includes material delivered into low-earth-orbit (LEO) for sale to operators and constructors of LEO infrastructure such as space stations, exotic materials factories, orbital hotels and satellite solar power stations. Some asteroidal material may be able to be delivered into Earth orbit for a cost which is very much less than Earth-launch cost. Some candidate materials are water (for use to make propellant), nickel-iron grains (to make construction material sheets and beams), and semi-conductors such as silicon and germanium (to make solar cells).

Due to dimishing terrestrial resources, a future terrestrial market for precious metals (platinum group metals and gold) may also exist, requiring delivery of asteroidal material to the surface of the Earth.

Thus there will potentially exist a profit-making opportunity for a resource developer who could develop a capability to recover space-based materials and return them for sale in LEO, to capture the developing in-orbit market at its inception.

NEA Resources, Accessibility, and Trajectory Planning. The NEA discovery rate is now quite high, above 200 per year, with a substantial number being 300 meters diameter or more.

NEAs are known to be rich in many important molecules and elements which are absent on the Moon. In addition, due to high lunar surface to LEO costs, asteroid-derived material is easier to deliver to Earth than moon-derived material. Mining, extraction, and processing methods for volatiles recovery and for metals recovery can be readily conceptualized and are being developed. The easiest to extract and most easily returned useful material is water. This can be extracted at the asteroid and some of it used as reaction mass (e.g. in a solar thermal steam rocket) to return the remainder to earth-orbit. It is believed that $\sim$50% of all NEAs may be water-bearing objects.

NEA accessibility depends on velocity change delta-v to inject into transfer orbit, plus the velocity change needed to rendezvous with the target. Global minima of delta-v values can be estimated, by several methods. There is a subset of about 100 NEAs that are easier to get to (lower delta-v) than soft-landing on the Moon. Delta-v for injection into a trajectory to return to Earth from some of these can be very low indeed some are under 1 km/s.

Ease of return depends on the asteroid departure delta-v, and on the hyperbolic velocity at Earth-return. Propulsive capture will be expensive inasmuch as it consumes otherwise-saleable returned volatiles. Lunar flyby gravity capture is suggested as a way to remove hyperbolic velocity, although it will place a time constraint on the return dates. Aerobraking is another alternative.

Analysing Project Feasibility. Project economics is driven by mission velocity requirements, by the propulsion system characteristics (particularly I_{sp}), and by project time duration and time-cost-of-money. The Net Present Value (or more accurately, the expectation NPV) depends on and is a function of: the delta-v required for return and capture into LEO, and the exhaust velocity of the propulsion system (these two factors determine how much of the extracted water gets used up as return trip propellant); the mass throughput efficiency of the remote miner (kg output per day per kg of equipment mass); the mission cycle time, i.e. the time duration from launch to product delivery in LEO (this is related to the period of the transfer orbit from Earth to the target and return, and to the duration of the mining season); the value of the product once delivered into LEO; and the market interest rate.

6.2 Further Work for Next Term

Use NPV as Figure of Merit for Space Mining Ventures. This work provides an outline for a rigorous approach to performing feasibility studies on asteroid and comet mining ventures. The concept of NPV should be used as a design-driver and reality check in project concept selection and development. NPV provides a way of sieving the concepts that will not survive economically. The NPV should be calculated for a large variety of possible projects, with both humans and non-humans. The NPV equation given in the paper will have to be expanded to include different mission designs.

Return to Earth Orbit. Methods of returning asteroid-derived material to Earth's surface were not encountered by the author. In the future, a more thorough search of the literature on this topic should be performed. The technical and economic feasibility of alternative methods for returning material to Earth's surface should be established.

Delta-V Calculations Using Alternative Methods. The propulsion burden necessary to move a large asteroid (10^3 - 10^6 tonnes) is enormous. Every effort should be made to lower the return delta-v. Previous "global minima" calculations using a patched-conics approach have been performed, but this considers only two-body gravitional effects. Recently, more advanced methods have been developed which consider three or more body effects. This method, known as the "coupled three-body" approach, can achieve delta-v savings of 50% compared to a Hohmann transfer (Koon, Lo, Marsden and Ross [1999]).

Additinally, for some situations, a patched-conics approach does not apply at all. The space surrounding the Earth-Moon L_1 point has recently been considered as a possible location for a space platform (Lo and Ross [2001]). A space structure near the well known cislunar libration point between the Earth and Moon, where gravitational and centrifugal forces balance, could operate as a space transportation node for lunar and planetary exploration. For commercial purposes, a space structure the Earth-Moon L_1 point could operate as a bulding platform for structures to be built from space resources, including asteroid-derived material. According to the author, no study has been performed of the delta-v necessary to transfer from an asteroid orbit to the Earth-Moon L_1 point (or any other Earth-Moon Lagrange point), due mostly to the failure of the patched-conics approach in this regime of motion.

A systematic calculation of optimal delta-v's for both the outbound and return tranfer to selected NEAs should be performed using the coupled three-body approach. Return to the Earth's surface, LEO, and Earth-Moon Lagrange points should be considered.

6.3 Funded Research Recommendations

NEA Population. A major problem is that only a small proportion of NEAs have been spectrally classified, hence their surface composition is not known. Major work is needed in order to define the mineralogically acceptable short-list. There is thus a need for more spectroscopic, polarimetry, IR data and other remote sensing (e.g. radar) information, to assess surface composition.

Mining, Extraction, and Processing Methods. There are many areas requiring study: anchoring into regolith on a body which has milli-g gravity; collection and handling material in milli-g gravity; thermal power requirements for adequate volatiles release; system integration and minimum mass for required throughput.

Mission Operations. Analyses of human for non-human operations should be performed. Control via teleoperation and trained machine intelligence will require successful developments in machine learning and robotics (e.g., neural net, fuzzy logic).

Propulsion, Power, and Systems Integration. Propulsion and power options reviewed thus far have focused on solar-thermal systems for the initial projects. Ultra-lightweight solar collector technology already exists. System integration has not yet even commenced but should be a straightforward engineering task.

7 Bibliography

Chamberlain, A. B. [2001] Near-Earth Object Program Office at the Jet Propulsion Laboratory (website) http://neo.jpl.nasa.gov.

Collins, P., et al. [1994] Commercial Implications of Market Research on Space Tourism, *19th International Symposium on Space Technology and Science, ISAS, Yokohama, Japan.*

Gertsch, R. [1984] Asteroid Mining, *Space Resources, NASA Publ SP-509* (eds. McKay and Duke), 1992 (Proceedings of NASA-ASEE Summer Study Workshop at California Space Institute, 1984).

Helin, E., and E. Shoemaker [1978] Earth Approaching Asteroids as Targets for Exploration, *NASA Conference Publ. 2053, Asteroids: an Exploration Assessment* (eds. Morrison and Wells).

Kargel, J. S. [1996] Market Value of Asteroidal Precious Metals in an Age of Diminishing Terrestrial Resources, in *Engineering, Construction, and Operations in Space V, Proc. of the Fifth Int'l Conf. on Space '96* (ed. S. W. Johnson).

Kargel, J. S. [1997] Semiconductor and Precious-Metal Resources of Metallic Asteroids, *Princeton Conference on Space Manufacturing*, Space Studies Institute.

Koon, W.S., M.W. Lo, J.E. Marsden and S.D. Ross [1999] Constructing a Low Energy Transfer between Jovian Moons, *Proceedings of the International Conference on Celestial Mechanics*, Northwestern University, Chicago, Illinois, to appear.

Koon, W. S., M. W. Lo, J. E. Marsden, and S. D. Ross [2000] Heteroclinic connections between periodic orbits and resonance transitions in celestial mechanics, *Chaos* **11**(2), 427–469.

Kuck, D. L. [1995] The Exploitation of Space Oases, *Princeton Conference on Space Manufacturing*, Space Studies Institute.

Lewis, J. S., K. N. Ramohalli and T. Triffet [1990] Extraterrestrial Resource Utilization for Economy in Space Missions, *International Astronautical Federation Conference.*

Lewis, J. S. [1991] Construction Materials for an SPS Constellation in Highly Eccentric Earth Orbit, *Space Power* **10**, 353–362.

Lewis, J. S. [1993] Logistical Implications of Water Extraction from Near-Earth Asteroids, *Princeton Conference on Space Manufacturing*, Space Studies Institute.

Lewis, J. S. [1997] Resources of the Asteroids, *Journal of the British Interplanetary Society* **50**, 51–58.

Lewis, J., T. Jones, and W. Farrand [1988] Carbonyl Extraction of Lunar and Asteroidal Metals, *Engineering, Construction, and Operations in Space* (eds. Johnson and Wetzel), American Society of Civil Engineers, 111–118.

Lewis, J. S., and S. Nozette [1983] Extraction and Purification of Iron-Group and Precious Metals from Asteroidal Feedstocks (AAS 83-236), *Space Manufacturing 1983*, Vol. 53 of Advances in the Astronautical Sciences, (eds. Burke and Whitt), American Astronautical Society, 351–354.

Lo, M. W. and S. D. Ross [2001] The Lunar L_1 Gateway: Portal to the Stars and Beyond, *AIAA Space 2001 Conference, Albuquerque, New Mexico, August 28-30.*

Nagatomo, M. [1996] An Approach to Develop Space Solar Power as a New Energy System for Developing Countries, *Solar Energy* **56**(1), 111–118.

O'Leary, B., M. J. Gaffey, D. J. Ross and R. Salkeld [1979] Retrieval of Asteroidal Materials, *Space Resources and Settlements* (NASA SP-428), 142–155.

Oxnevad, K. [1991] An Investment Analysis Model for Space Mining Ventures, *International Astronautical Federation Conference.*

Sonter, M. J. [1996] The technical and economic feasibility of mining the near-earth asteroids. *MSc (Hons) Thesis*, Dept. of Physics and Dept. of Civil, Mining, and Engineering, University of Wollongong, NSW, Australia.

Sonter, M. J. [1997] The technical and economic feasibility of mining the near-earth asteroids. *Acta Astronautica* **41**(4-10), 637–647.

Sonter, M. J. [2001] Near Earth Objects as Resources for Space Industrialization *Solar System Development Journal* **1**(1), 1–31.

Turner, A. [2001] *Houston Chronicle*, 28 October 2001, http://www.chron.com/cs/CDA/story.hts/metropolitan/1107492.