The Technical and Economic Feasibility of Mining the Near-Earth Asteroids

M J Sonter. Presented at 49th International Astronautical Federation Congress, Sept 28 – Oct 2, 1998, Melbourne, Australia. Posted with permission of the author.

Abstract

Future large scale commercial activities in space will require raw materials obtained from in-space sources rather than from Earth, to overcome the high cost of Earth launch. This paper reviews the prospectiveness of non-terrestrial resources and notes the competitiveness of Near-Earth-Asteroids c.f. the Moon and Phobos or Deimos in terms of accessibility and likely resources. Astronomical work over the last fifteen years has increased the number of known Near Earth Asteroids (NEAs) from about 30 to about 400. Discovery rate of NEAs is now about 50 per year.

Asteroid “geography”: NEAs are classified by orbital parameters into Apollos, Amors, and Atens; in addition, the “Arjunas” are the group of small objects in very Earth-like, and therefore very accessible, orbits. Accessibility is defined in terms of velocity requirements (delta-v) for outbound and for return trajectories. Approximately 10% of NEAs are more accessible than the Moon, and maybe 50% of these are likely to be potential orebodies.

Asteroid “geology” has advanced dramatically in the last decade, via spectroscopic and dynamical studies of asteroids and comets, and meteorite studies; reasonable inferences can now be made from asteroid types defined by spectral properties to probable surface mineralogy. Many asteroids may be “volatiles bearing”, containing clays, hydrated salts, and hydrocarbons. It also now seems that there are dormant cometary bodies within the population of NEAs. These are likely to contain remnant primordial ices within their cores, making them possible sources of volatiles for future space industry.

Resources which would appear to be readily recoverable are thus water and other volatiles, for manufacture of propellant in orbit; and nickel-iron metal, for construction in orbit.

There have been various concepts proposed for mining and retrieval to low-earth-orbit of materials from NEAs, but methods of comparison of the

economic feasibility of competing mission concepts are not well-developed. In-situ production at the asteroid of the propellant needed for materials return is an important “enabling” concept. This paper develops methods for comparison of different asteroid mining concepts, and for choosing between various product, process, mission, and engineering alternatives, so as to maximize likely project economic feasibility.

Application of celestial mechanics shows that (i) simple estimates of “global minimum” delta-v can be made; (ii) low-energy opportunities occur at approx 2-yearly intervals, for many NEAs; (iii) long synodic periods militate against multiple-return mining missions; (iv) Earth-return hyperbolic velocity should be kept low; (v) high-eccentricity targets require Hohmann transfers, and a short mining season at aphelion; (vi) low-eccentricity targets may use continuous-thrusting propulsion, and extended mining season. There is a growing subset of targets that are intermittently accessible for an outbound delta-v of under 6 km/s, and offering return departure delta-v under 2 km/sec.

Mining and processing system choices depend on the assumed regolith mineralogy and bulk handling properties, and on the assumed subsurface composition and properties. Process options are (i) in-situ fluidization; (ii) mechanical collection and thermal or magnetic separation; (iii) carbonyl process. Equipment mass estimations for volatiles extraction suggest total processing system mass of less than 5 tonnes for a teleoperated / autonomous miner mission to return 1000 tonnes to LEO.

Sensible and politically achievable propulsion and power system choices are restricted to (i) solar thermal steam rocket; (ii) solar photovoltaic arcjet; (iii) solar photovoltaic massdriver.

As for terrestrial mining projects, the Expectation (probabilistic) value of the Net Present Value is a crucial unifying concept for evaluating competing mission options. By testing system choices for their effect on NPV, one can arrive at project design choices that are optimized. The NPV formula can readily be expanded in terms of the astrodynamic and rocket equation parameters, and the parameters describing the mining and processing equipment and performance.

Conclusions: Advances in asteroid astronomy and discovery rates give confidence that there are many accessible potential orebodies among the Near-Earth Asteroids. Mining and metallurgical options exist that are simple and robust. The use of NPV is crucial in project concept development. A teleoperated miner for return of volatiles from NEAs is economically feasible, using present technology, with an initial market of about 1000 tonnes per year. — **Asteroid mining is very close to technical and economic feasibility**.

Introduction

The technology needed to avert comet or asteroid impact is similar to that needed to recover the essentially unlimited resources contained in these bodies. Thus it is desirable to develop asteroidal resources, both to achieve wanted outcomes (namely space industrialisation, species security, and long term prosperity) and to build the capacity to avert disaster.

This paper reviews concepts for mining the Near-Earth Asteroids for supply of resources to future in-space industrial activities. It discusses a standard approach for carrying out Technical and Economic Feasibility Studies on proposals for asteroid resource recovery projects.

Potential Commercial ‘Drivers’ for Space Industrialisation

The industrialisation and settlement and of space is likely to be brought about primarily by increasing commercial activities in space, including the following:

Expansion of trunkline communications, direct broadcast TV, navigation, remote sensing, and meteorological services worth several billion dollars per year from an in-space satellite assets investment estimated to be about 50 billion dollars. LEO satellite constellations will roughly double the annual income of these services, over the next decade.

Commercial space-based production of high value pharmaceuticals, semiconductors, ultra-pure crystals, and exotic alloys. Although research work has been done on Mir (in orbit since 1986), commercialisation has been severely delayed by the loss of access to the Space Shuttle, after the Challenger disaster.

The concept of satellite solar power stations (SSPS) is again receiving active consideration, after a decade of disinterest: the Japanese are planning an equatorial orbit SSPS pilot plant, titled SPS2000, orbiting at 1100km altitude, of mass 200 tonnes.

The feasibility of space tourism is being promoted by Patrick Collins and colleagues in Japan. Their projections show that at a launch cost of $200/kg the space tourism market will grow rapidly to several billion dollars per year.

Hotels in orbit will be needed, to cater for 10,000 person accommodation after some years. Shimizu Corp has developed a plan for such an orbiting hotel, of mass 6000 tonnes.

The future market for mass-in-orbit

As a result of the activities described above, *we can hypothesise a conceptual future market for mass in low-earth-orbit* (i.e. metals for construction, volatiles to make propellants for stationkeeping and for deorbit burn, and unprocessed mass for ballast and shielding against cosmic radiation). The size and rate of development of this future in-orbit market for materials could easily exceed 1000 tonnes per year by 2010, growing exponentially to tens of thousands of tonnes per year if any of the larger-scale activities “take off”.

The large reductions in launch cost promised by new launcher concepts (from the present $10,000/kg down to something like $500/kg) will prompt a huge growth in the launch market, probably driven initially by tourism.

The Accessibility and Competitiveness of Non-Terrestrial Resources

The natural resources in space include metallic nickel-iron alloy, silicate minerals, hydrated minerals, bituminous material, and various volatiles, including water, ammonia, carbon dioxide, methane, and others. These have all been identified either in meteorites, or spectroscopically in asteroids and comets. Any industrial development in space requiring more than about a thousand tonnes of structural mass or propellant per year will direct attention to these materials as **ores**, *in the true mining engineering sense*.

Raw materials retrieved from non terrestrial sources need not attract the high “airfreight” costs referred to above. This is because the energy requirement to return material from many of the possible target near-earth asteroids is much less than the energy requirement to launch from Earth.

In addition, the freedom to deliver the velocity change non-impulsively, means that low power propulsion systems may be considered, and this allows a system that uses solar power and derives its return-journey propellant from the target body, such as asteroidal volatiles.

In-Situ Propellant Production

The mission velocity delta-v needed to reach selected “near earth” low delta-v target asteroids is not much greater than that needed to place a communications satellite in geosynchronous orbit (GEO). 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.**

The effect of the above concepts, is that some asteroidal material may be able to be delivered into Earth orbit for a cost which is very much less than Earth-launch cost.

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 low-earth-orbit*, to capture the developing in-orbit market at its inception.

Orebodies in Space

It is necessary to identify the requirements that must be satisfied by an Earth-approaching asteroid or short-period comet to make it an “orebody” in the mining engineering sense: that is, to identify it as a resource source that can support an economic materials retrieval project.

These economic and technical requirements are:

1. there needs to be a *market* for the products
2. need adequate *spectral data* indicating presence of the desired materials
3. check that *orbital parameters* give reasonable accessibility and mission duration

4. development of feasible *concepts for mining & processing*
5. development of feasible *retrieval concepts*
6. require positive economic *Net Present Value*, using the chosen engineering concepts.

Like terrestrial mining projects, we find that each asteroidal resource project will have its own idiosyncrasies, reflected here in the alternative mission trajectory profiles to be considered.

The following diagram is intended to show how these concepts interact.

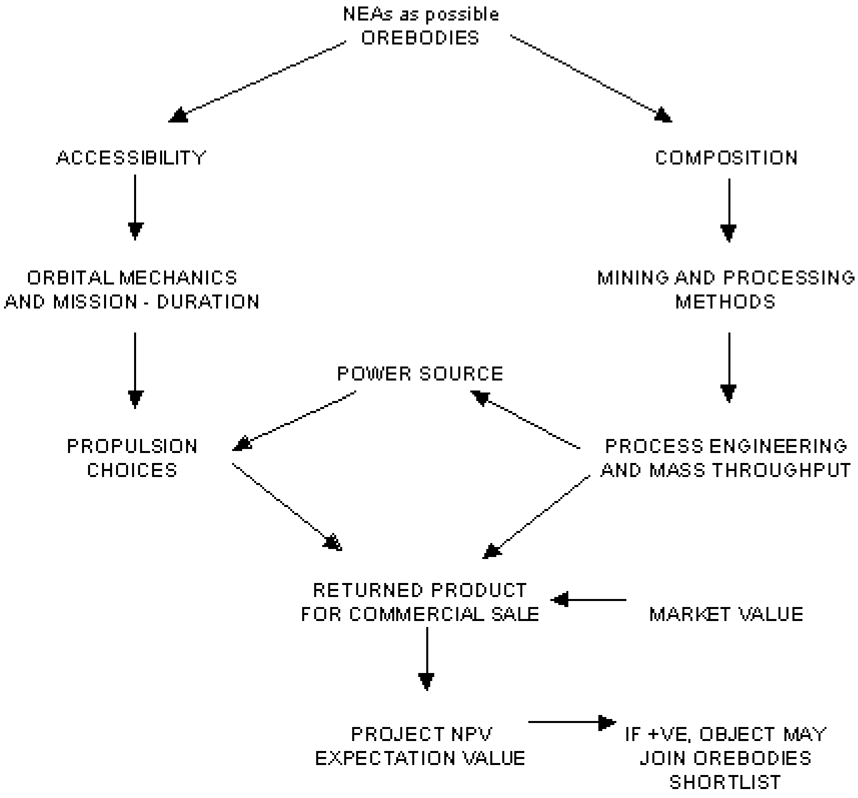

Figure 1: Concepts Flowchart

The above flowchart describes the methodology which has been developed for determining the technical and economic feasibility of a hypothetical asteroid mining project.

Review of Asteroid Resources and Accessibility

Resources: Astronomical work over the last fifteen years has increased the number of known Near Earth Asteroids (NEAs) from about 30 to about 430. Discovery rate is now in excess of 50 per year. Asteroid geology has also advanced dramatically in the last decade, drawing on spectroscopic and dynamical studies of asteroids and comets, and meteorite studies, and 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 near-earth asteroids may be “volatiles bearing”, containing clays, hydrated salts, and hydrocarbons. It has also become clear that there is a continuum from asteroidal to dormant cometary bodies, within the population of NEAs.

A matrix of alternative asteroid types and proposed products has been developed, from consideration of meteorite types and project options.

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meteorite mineralogies	—–>	**spectroscopically inferred asteroid geology**	—–>	**possible mining and processing c**	—->	**desired product**

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Table 1 : Matrix of spectral type, inferred mineralogy, and potential products

Type	Inferred Mineralogy	Product
C, D, P	clay, organics, ice at depth?	volatiles: H2O, CO2, CH4
B, G, F	clay, silicate, ?limestone, ?Nickel-Iron metal	volatiles: Nickel-Iron metal
Q, S, M	silicates, Nickel-Iron metal	metal, silicates, Platinum Group Metals (PGMs)

In the case of those bodies which are dormant or extinct comets (there are several likely candidates), there may be remnant primordial ices within their cores, and hence they are possible sources of volatiles for future space industry.

Accessibility: In space, the parameter which determines how easy or difficult it is to deliver mass from one orbit to another, is not distance, but is the required velocity change, delta-v, needed to perform the transfer.

From comparison of velocity increments for different transfers, it can be seen that it is much easier to go from low earth orbit (LEO) to nearly anywhere in the inner solar system than it is to get into orbit from the earth’s surface.

Table 2: Mission Velocity Requirements (delta-v)

Earth surface to LEO	8.0 km/s
Earth surface to escape velocity	11.2 km/s
Earth surface to GEO	11.8 km/s
LEO to escape velocity	3.2 km/s
LEO to Mars or Venus transfer orbit	3.7 km/s
LEO to GEO	3.5 km/s
LEO to HEEO	2.5 km/s
LEO to Moon landing	6.3 km/s
LEO to Near Earth Asteroid	approx 5.5 km/s
Lunar surface to LEO (with aerobraking)	2.4 km/s
NEA to Earth transfer orbit	approx 1.0 km/s
Phobos / Deimos to LEO	8.0 km/s

Likely low delta-v targets for initial resource development are the “Earth-Approaching” Apollo, Amor, or Aten type asteroids; the moons of Mars, Phobos and Deimos; the asteroid 1990MB Eureka, which is a Mars Trojan; any hypothetical Earth-Trojan asteroid; and any of the Earth-orbit-hugging “Arjunas”.

Asteroid “geography”: NEAs are classified by orbital parameters into Apollos, Amors, and Atens. Approximately 10% of NEAs are more accessible than the

Moon in terms of required mision velocity for outbound and return trips, and at least 50% of these are likely to be potential orebodies.

Mission Plans and Trajectories

Application of the concepts of celestial mechanics show that

1. simple estimates of “global minimum” delta-v can be made, by several methods;
2. the launch windows for these “global minimum” opportunities are infrequent, but somewhat higher energy local minima occur at approx 2-yearly intervals, for most NEAs;
3. long synodic periods requirements militate against multiple-return mining missions;
4. Earth-return hyperbolic velocity should be kept low;
5. high-eccentricity targets imply Hohmann transfers, and short mining season at aphelion;
6. low-eccentricity targets may use continuous-thrusting propulsion, and extended mining season.

There is a growing subset of targets that appear to be intermittently accessible for an outbound delta-v under 6 km/s, and offering return departure delta-v under 2 km/sec.

When we consider the alternative out-and-return trajectories to different target bodies, taking into account allowable stay times for resource extraction, it is found that five different “mission trajectory types” are identified. This is because:

- targets may be in ‘low’ or ‘high’ eccentricity orbits;
- targets may have perihelion inside or outside earth orbit;
- transfer from target may be by Hohmann ellipse or by ‘continuous thrusting’;
- mining season may be ‘short-term’ or extended;
- mining season may be ‘single-mission’ or ‘repeating’;

- if ‘short-term’ mining season is required, it may be aphelion-centred or perihelion-centred.

Orbit-matching and synodic period constraints militate against a general “pro-forma” approach to trajectory design. For example, it is necessary for the payload on its return trajectory to intersect Earth orbit when Earth is nearby (and not on the other side of the sun). From a review of the orbital geometries we can see that there are various **Alternative Mission scenarios** available:

“Apollo-Type” (Apollo or high-eccentricity Amor asteroids): Objects with “high” eccentricity, low-inclination orbits demand Hohmann transfer for both outbound and inbound trajectories, because of their relatively high delta-v requirement. Mining season is restricted to a short period during aphelion; delta-v for return 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 delta-v(out); a “short” aphelion-centred mining season, (for example, a 3 month mining stay); and a post-aphelion departure for Earth-return, with approx 3 month thrusting, for minimum delta-v return .

There is a need to destroy a relatively large return (hyperbolic) arrival velocity. Lunar flyby is of partial use only, because it can remove only 1.5 km/s. This criterion, i.e., the delta-v requirement to achieve Earth-capture, is in fact more demanding than the asteroid-departure delta-v requirement.

Mission duration must approximate the period T of 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 and impact negatively on Project NPV. To minimise delta-v (deep space), the object’s orbit should be “Earth-grazing”, i.e., q = 1.0 AU.

Short period comet missions: 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, and by the constraint of a very short mining season.

“Aten-Type”: High-eccentricity Atens: This mission type assumes a Hohmann transfer to rendezvous with the target asteroid at its perihelion, with a near-aphelion departure after half an orbit stay time. Post-perihelion departure is ruled out, because (i) this gives inadequate mining season duration; (ii) there is a phasing requirement : T of transfer orbit << 1 yr, so Earth will not ‘be there’ if return craft sets out from target’s perihelion.

An alternative mission profile contemplates an aphelion arrival (requiring high delta-vds 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 delta-v(out) and delta-v(return), and total time of mission.

This implies a “selection rule”: [*T/2 of transfer orbit to target’s perihelion + T/2 of target’s orbit + T/2 of transfer orbit from target’s aphelion to Earth*] is the mission time, and this must approximate to 1.5 years.

Arjunas and low-eccentricity Amors (“Arjuna-Type’): The “Arjunas”, and some Amors, have very nearly circular orbits. Such close, low eccentricity, low inclination NEAs, may be favourable for spiral, non-Hohmann returns; a characteristic of these trajectories is the ‘softness’ of the launch window for return.

Slow spiral return implies longer mining season, and hence less demanding specifications on mining, processing, and propulsion equipment, and on solar collector. Note that spiral return trajectories can be designed to deliver the payload at very small vhyp (hyperbolic return velocity), because the spacecraft trajectory can be made tangent to the Earth’s orbit. Such low vhyp implies easy capture into HEEO (Highly Elliptical Earth Orbit) by lunar flyby.

Higher-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 impulse demand, ((delta-v(inclin)) (0.5 (i km/sec.)), so timing of mission phases with respect to Ascending / Descending Nodes is important.

Return to Earth Orbit Capture (LEO or HEEO): 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:

1. rely on propulsive braking, using some of the Asteroid-derived propellant; this is simplest, but undesirable, as it reduces the quantity of material that is available for sale.
2. rely on aerobraking, using an Earth-fabricated, LEO-fabricated, or asteroid-fabricated aerobrake. May be metallic or refractory silicate. The problem is, to fabricate an aerobrake on an asteroid, by remote means, adds another level of complexity.
3. use lunar flyby to remove hyperbolic delta-v. This will naturally insert the returning craft into HEEO (Highly Elliptical Earth Orbit) 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.

Thus, the most desirable targets for lunar flyby capture are those asteroids with aphelia less than (say) 1.25 AU, or perihelia more than (say) 0.8 AU.

Arguments against Multiple Trip Scenarios:

Repeated returns to the same target asteroid have in general been discounted because:

1. the high required Internal Rate of Return means that sales receipts of subsequent missions are heavily discounted;

2. it is assumed that any later mission to the same target will be severely “off-optimum” compared with the first, to the extent that a different target will be preferable;
3. the operator will want to recover the remote miner and refurbish and upgrade it;
4. it is assumed that lessons learned after the first mission will dictate modifications to both the equipment and the mission planning.

Conclusions regarding Mission Trajectory Types:

1. there are several mission types that can be identified, each with implications for length of mining season and total mission duration;
2. Earth-return hyperbolic velocity is a major mission delta-v demand;
3. synodic considerations suggest that “multiple return” missions to a permanently-emplaced mining facility are generally not competitive.

Concepts for Mining, Processing, Power, and Propulsion:

The design concepts discussed here involve the design for the simplest, minimum mass and cost product return system possible, namely a remote controlled or automated mining and processing plant. Requirements and engineering choices for mining and processing depend on the assumed regolith mineralogy and bulk handling properties, and on the assumed subsurface composition and properties, if the desired material is to be recovered by drilling. See Table below:

Table 3 Possible Products and Sources

Type	Product and Process	
	Volatiles	Structural materials
“cryptocometary”	H2O, CO2 in-situ fluidization	—

carbonaceous	H2O, CO2 thermal dehydration	NiFe metal magnetic separation
ordinary chondrite	—	NiFe, silicates magnetic separation
metallic	—	NiFe, Platinum Group Metals carbonyl process

Engineering Choices can be identified as follows:

product:	water; metal; gases; silicates; PGMs.
process:	drilling with insitu melt and extraction; heat, dehydrate, and condense; electrostatic / magnetic extraction ; carbonyl extraction.
target type:	extinct or dormant comet; overtly carbonaceous or hydrous asteroid; overtly cometary; S-type asteroid; overtly metallic asteroid.
power:	solar thermal; nuclear thermal; photovoltaic.
propulsion:	steam rocket; mass driver; arcjet.
control:	telepresence; machine autonomy; manual.

Propulsion and power choices are linked; only a subset is technically and politically viable. In-situ propellant production at the asteroid constrains the system choices to those below:

Table 4 Propulsion and Power Choices

Power	Propulsion			
		steam rocket	arcjet	**mass driver**
	solar thermal	Yes	No	No
	solar PV	No	Yes	Yes
	nuclear	Yes (no)	Yes (no)	Yes (no)

Assuming that the initial target resource will be water and that the target asteroid type will therefore be ‘cryptocometary’ or carbonaceous, the power-propulsion choice ‘boils down’ to the steam rocket with solar thermal power, following the concepts developed by Shoji and others.

The process choice may be recovery by drilling through surface crust and in-situ fluidization of subsurface volatiles (Kuck Process), or soil collection and extraction of volatiles by heating.

Kuck Insitu Extraction Process: Kuck’s process requires much less in terms of system mass than the soil 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 or porosities; (iii) there is the risk of blinding or clogging of the drillfluid return pathway, or of the fluid recovery and conditioning system; this clogging could be by fine sediments, clays, salts, waxes, or reaction products.

Regolith Devolatilization Process: The soil devolatilization process requires a more complex materials handling plant, and must be designed for an approximately ten-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. The equipment will comprise a collector, soil pressurizer, grinding mill and heater, solid-vapour 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 200 may be achieveable. 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.

Project Feasibility and Economic Selection Criteria

Several authors note the important fact 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 & Parks, 1985, suggest that it is necessary to achieve an internal rate of return (IRR) in excess of 30% per annum, to offset the perceived risk!!

There have been various concepts proposed for mining and retrieval to low-earth-orbit of materials from NEAs, but it has been noted in the literature (Cutler & Hughes, 1985; Lewis, Ramohalli & Triffet, 1990; Ramohalli, Kirsch, & Priess, 1994; 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.

Some observations from these papers are as follows:

"We need some way of *quantitatively assessing the merit of a very large number of (competing) combinations of minesites, ores, processes, products, and destinations*….. (There is) the very important task of identifying and

evaluating the “big picture”. How can one make these various technologies mesh together to give the best overall system?” – (Lewis, Ramohalli, & Triffet, 1990 – this author’s italics).
Knut Oxnevad, in “An Investment Analysis Model for Space Mining Ventures” (1991):

“Through extensive sensitivity analysis, it was… shown that launch cost (was) *not* a critical parameter.”

Traditional Mass PayBack Ratio “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.” Oxnevad went on to point out that rigorous economic comparative analyses should emphasise NPV rather than MPBR.

Cutler & Hughes, 1985, made similar points:

“high MPBR is not particularly important. *Low initial capital* ***is*** *important*…. Optimising selected physical parameters such as delta-v or Isp does *not* in general lead to most economical system.” (present author’s emphasis)

“*A general economic methodology to evaluate schemes for extraterrestial resource utilisation is needed. At the moment no standardised method exists for researchers to compare their schemes on a common basis*. They are not able to evaluate the effects of specific innovations. Each prior study calculated costs differently and set up a different manufacturing scenario without isolating the economic effects of each system component. Thus, quantitative comparison between these studies is not possible.”

It is thus important to find a method to **compare the financial feasibility of competing space mining mission proposals**, such as:

- volatiles from comet core (aphelion mission)
- volatiles from comet core (perihelion mission)

- volatiles from C-type asteroid (aphelion mission)
- metals and volatiles from C-type asteroid
- metals from M-type asteroid
- PGMS only from C-type asteroid
- LOX, LH2 from lunar polar ice
- bootstrapping vs non-bootstrapping missions to NEAs
- non-bootstrapped raw mass return from an Arjuna
- volatiles from Phobos or Deimos

In order to carry out these comparisons, it is necessary to **expand the formula for Net Present Value in terms of astrodynamic and the Rocket Equation variables.**

To summarise, there is an apparent need, identified by several workers, for a robust general approach to comparing hypothesised space mining projects; and for performing realistic feasibility assessments. *This approach necessarily addresses economic and quantitative risk assessment issues.*

As is now clear from earlier discussion, much study is needed to define realistic project alternatives, including :

- target asteroids / comets
- propulsion methods and propellants
- power sources
- materials to be reclaimed
- materials reclaim and processing methods
- guidance, navigation, and control, both outbound and return
- autonomous control of mining and processing activities
- sizing of minimum feasible project, and
- financial considerations

These choices are interrelated, as selection of a particular option in one area introduces constraints in the other areas. Also, different levels of knowledge and technical maturity apply to the various options. Mechanisms for ensuring political acceptance of a right to mine the resource are also critically important.

NPV Discussion and formula derivation

Economic “figures of merit” used to assess financial feasibility of proposed projects are:
Payback Period (= Net Investment / Net Yearly Cash Benefit) for quick analysis, and:
Net Present Value, as a more accurate measure of project merit over a project time period of (say) up to 10 years. Internal Rate of Return (IRR) is the discount rate at which NPV equals zero, i.e., is the implied interest rate that the project pays its owners.
Mining companies (and more generally, banks and other large investors) regard a project that can pay back its capital in 3 or 4 years as attractive, and one which will take 10 or more years as unattractive. *Considerations of attaining strategic political or market positioning may however override these rules of thumb.*
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.
It is necessary to carry out a Sensitivity Analysis, to answer the questions:

- what happens if costs to LEO drop to (say) $500/kg? (or $200/kg?)
- what if lunar LOX, or even LH2 are deliverable to LEO at (say) $500/kg?
- what if market size is only 500 tonnes per year in LEO?
- if we increase output by 50 or 100% can we still sell it?

A Reliability or Probability-of-Success Analysis is also needed:
A good Figure of Merit for a risky commercial enterprise is “*expectation value of NPV*“, where the expectation value of NPV, its most likely value, weighted by probability of outcome, is:

$(NPV)_w = NPV_1 \cdot p_1 + NPV_2 \cdot p_2 + NPV_3 \cdot p_3 + \ldots..$

where probabilities p1, p2, p3, … etc add to = 1.

Net Present Value Derivation & Calculation Process

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

PV = R × (1+i)-n where i is the interest rate paid for risky investment capital.

NPV in the comet or asteroid mining case depends on:

- *cost* to launch and conduct the mission
- *mass* returned and what you can sell it for
- *time* it takes to accomplish

Whilst outbound delta-v is not critical, except within the constraints of the launcher capability, return delta-v must be minimised; and duration of mining season should be maximised, consistent with minimising total mission time and maximising mass returned. The implications for asteroidal or cometary resource return projects are that missions taking longer than (say) three years will have to have very good MPBRs (mass payback ratios), in order for the NPV to be positive.

For the “Apollo-type” asteroid or comet mining case, with a single payload return, using a solar-thermal steam rocket, the formula for NPV can be expanded as follows:

For a single payback receipt, NPV = R × (1+i)-n – Capital

It can be shown after expansions that

NPV = $/kgorbit × Mmpe × f × t × %recov × e-delta-v/ve × (1+i)-(a3/2) – (Mmpe + Mps + Mi&c) × $/kgmanuf + budget × n)

Note that the values delta-v must be determined from celestial mechanics for the particular trajectories chosen.

Process for determining NPV

This applies to mining missions with short stay times centred around aphelion or perihelion, with Hohmann transfers out and back; it assumes that the thrusting time on the return transfer is short c.f. the orbital period of the transfer orbit, i.e., less than (say) 20 degrees of arc. It also assumes that capture into earth orbit is via lunar flyby to remove hyperbolic velocity. The delta-v to go from HEEO to LEO has not yet been considered.
The process for determining feasibility is thus as follows:

1. set required payload to be returned.
2. find delta-v (return) from target body using Hohmann transfer calc or otherwise.
3. adjust for delta-v reqd for inclination change (i in degrees):
4. from propulsion system Isp, calculate propellant requirement;
5. determine mining stay time, and assume some recovery (say 10% of bulk feed); hence determine power reqd by miner to process reqd quantity of volatiles.
6. using same power source, derive “burn time” curve, and from it check mass returned.
7. calculate elapsed time from period of transfer orbit.
8. insert all variables into formulae above, and calculate Expectation NPV for the success scenario, realising that the probability of success is less than unity.

Conclusions

The findings of the author’s studies into asteroid mining feasibility are therefore as follows:

1. Some Near-Earth Asteroids offer very promising targets as future orebodies 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.

Such space resources will have to compete against Earth-launched resources. This may be made possible by applying the concepts of in-situ propellant production.

2. Asteroid – comet genesis of target body determines whether regolith-reclaim or drill-and-melt is to be the recovery process of choice. A matrix of mineralogy / product / process choices was developed.

3. Near-Earth Asteroid geography is characterised by orbit location and type. The discovery rate of NEAs is now quite high, and there are an increasing number of “likely” targets being identified.

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’.

4. Target 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. When serious work begins on asteroid mining projects, actual date-specific mission velocity requirements will have to be calculated, for the various project alternatives.

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. Further work is needed in ‘capture technology’.

5. Considerations of mission profiles suggests a classification into five types:

- high-eccentricity, aphelion mining season (“Apollo-type”)
- “Aten-type”

- spiral low thrust (low-eccentricity Amor or “Arjuna type”)
- high inclination, low eccentricity
- high-e, perihelion mining season (“Comet-type”)

In general, return missions to a particular body are not apparently advantageous, c.f. a new target.

6. Mining and processing methods can be readily conceptualised. However, 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; minimum temperature and most rapid heat pulse for adequate volatiles release; system integration and minimum mass for required throughput.

Control via teleoperation and trained machine intelligence will require successful developments in neural net and fuzzy logic machine learning and robotics.

7. Propulsion and power options review tends to focus on solar-thermal systems for the initial projects; PV power and arcjet are not excluded. Ultra-lightweight solar collector technology already exists. System integration has not yet even commenced but should be a straightforward engineering task.

8. Project economics is driven by the mission velocity requirements, by the propulsion system characteristics (particularly Isp), and by project time duration and time-cost-of-money.

A cost delivered into LEO of probably $200/kg or so will be necessary for space raw materials resources recovery to be a viable competitor against Earth-launch cost in the first few decades of the next century.

A “spider diagram” has been developed which clearly shows the inter-relationship of all relevant variables. This, together with the formulation of project Net Present Value in astronautical and celestial mechanics variables, enables a systematic ‘roadmap’ approach to project feasibility determination.

In conclusion, this work provides a rigorous approach for performing Feasibility Studies on the asteroid and comet mining ventures of the early years of the next century, and in addition shows how NPV can be used as a ‘design-driver’ and reality check in project concept selection and development.