Solar System Development Journal (2001) **1**(1), 1-22 http://www.resonance-pub.com
ISSN:1533-7405

NEAR EARTH OBJECTS AS RESOURCES FOR SPACE INDUSTRIALIZATION

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(Received ....)

1. INTRODUCTION

The Near Earth Asteroids are potential impact threats to Earth, but also a particularly accessible subset of them does provide potentially attractive targets for resources to support space industrialization. Robust technical and economic approaches to evaluation of the feasibility of proposed projects are necessary for assessment of such space mining ventures. This paper discusses the technical engineering and mission–planning choices and shows how the concept of probabilistic Net Present Value can be used to optimize these choices, and hence select between alternative asteroid mining mission designs.

The generic mission reviewed envisages a lightweight remote (teleoperated) or semiautonomous miner, recovering products such as water or nickel-iron metal, from highly-accessible NEAs, and returning it to Low Earth Orbit (LEO), for sale and use in LEO, using solar power and some of the recovered mass as propellant.

Some of the technologies needed to avert comet or asteroid impact are similar to those needed to recover the diverse resources contained in these bodies. Thus it is desirable to develop this technology, and asteroidal resources, both to achieve space industrialization, 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 identifies Expectation Net Present Value as the appropriate measure for determining the technical and economic feasibility of a hypothetical asteroid mining venture, just as it is the appropriate measure for the feasibility of a proposed terrestrial mining venture. In turn, ENPV can obviously be used as a 'design driver' to sieve the alternative options, in selection of target, mission profile, mining and processing methods, propulsion for return trajectory, and earth-capture mechanism.

2. POPULATION OF TARGET BODIES

Recent progress in asteroid search programs (especially LINEAR, www.ll.mit.edu/LINEAR/) has been spectacular. According to Dr David Morrison, in the latest issue of his NEO Newsletter (dmorrison@arc.nasa.gov), there are now about 1400 identified NEOs, defined as objects whose orbits have a perihelion less than or equal to 1.3 AU. Of these, about 300 are classified as PHAs (Potentially Hazardous Asteroids), meaning that their orbits come within 0.05 AU (7.5 million km) of the Earth's. Of the total 1400 known NEOs, some 500 are of absolute visual magnitude less than 18, and therefore nominally of diameter larger than 1 kilometre. This recently derived number is larger than had previously been considered likely.

Estimates based on the serendipitous rediscovery rate indicate that the total population of ">1 km bodies" within the NEAs is now at least 1000, and the total population of ">100 metre bodies" is now thought to be in the range 100,000 to 200,000 (Lewis, 1993)[1] Logistical Implications of Water Extraction from Near-Earth Asteroids, SSI Princeton Conference)

Assessments originally performed by Lau and Hulkower (1985)[2], and later by Lewis (1993), indicated that something like 10% of all NEAs are more accessible, energetically speaking, than the Moon, and are very much easier to return from, than the Moon. These estimates were recently reviewed by the present author, using the Shoemaker-Helin formulae for estimating the probable likely minimum delta-v for Hohmann transfers to and from these bodies (Helin & Shoemaker 1978)[3], and show that we can now identify about 90 specific named bodies which are more accessible than the Moon (viz, 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 (very) few have outbound d-v's under 4.5 km/s. (See Tables attached as Appendix) Similarly, a few have d-v's for return departure of the order of 1 km/s.

Since the Tunguska explosion, now believed to have been caused by atmospheric breakup of a 60 metre diameter comet remnant (Report of the UK Task Force on Near Earth Objects, 2000**)**, delivered about 20 Megatons of explosive energy, and given the likelihood that such impacts are more frequent than was first considered, (CCNet : http://abob.libs.uga.edu/bobk/cccmenu.html) it can be seen that there is indeed a serious need to attempt to find and track all of these bodies, including the many hundreds of thousands in the smaller size ranges, and indeed also to begin studies aimed at engineering deflection methods (Gehrels, 1994)[4]. Two comments should be made in passing: Firstly, the most likely scenario in which humanity will be faced with the necessity to 'do something' will be the discovery of a relatively small body, maybe a year or so prior to impact. The 10 km planet busters are rare, the 'Tunguskas' are much more likely. Secondly, much of the science and engineering relevant to working out how to deflect these bodies will also be directly relevant to working out how to extract resources from, and otherwise exploit them, and vice versa. For example, the main obvious alternative to nuclear explosive deflection would be to emplace a remote miner and rocket propulsion assembly on the threat body, which would extract and use the asteroidal material as reaction mass, to deflect the body's trajectory. Thus, technologies for converting asteroidal mass into reaction mass will 'enable' both a highly controlled, 'calibrated', gentle deflection capability, and also mining and resource recovery. These propulsive methods might include solar thermal steam rocket, mass driver, or regolith rocket technologies.

3. THE VARIETY AND COMPETITIVENESS OF ASTEROIDAL RESOURCES

Near Earth Asteroids are of extremely variable and wide-ranging compositions, according to interpretations based on spectroscopic studies and on 'ground truth' from meteorites (Resources of Near-Earth Space, Lewis, Matthews and Guerrieri, University of Arizona Press, 1993)[5]. They include stony silicates, with enhanced levels of semiconductors and of Platinum Group Metals (Gaffey & McCord, 1976[6]; Kuck, 1979)[7]; bituminous or carbonaceous material - bearing bodies (e.g., Zuppero, 1996)[8]; dormant or extinct comets with remnant ices and clay minerals; and reduced metallic bodies, composed in large part of

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[1] Lewis JS: *"Logistical Implications of Water Extraction from Near-Earth Asteroids",* **Space Studies Institute Princeton Conference**, 1993.

[2] Lau and Hulkower: *"On the Accessibility of Near-Earth Asteroids"*, **AAS-AIAA Astrodynamics Conference**, 1985. (paper AAS 85-352)

[3] Helin & Shoemaker, *"Earth Approaching Asteroids as Targets for Exploration"*, in **NASA Conference Publ. 2053, Asteroids: an Exploration Assessment**, ed Morrison and Wells, 1978.

[4] Gehrels T: *"Hazards Due to Comets and Asteroids"*, University of Arizona Press, 1994.

[5] Lewis Matthews & Guerrieri: *"Resources of Near-Earth Space"*, **University of Arizona Press**, 1993.

[6] Gaffey & McCord: *"Asteroids: a Source of Natural Resources for Terrestrial and Extraterrestrial Applications"*, **Lunar Utilization Conference**, 1976.

[7] Kuck DL: *"Near-Earth Extraterrestrial Resources"*, **in Space Manufacturing Facilities 3, AIAA**, 1979.

[8] Zuppero A; *"Discovery of Abundant Accessible Hydrocarbons Nearly Everywhere in the Solar System",* **in Space 96, The Proceedings of the 5th International Conference on Engineering, Construction, and Operations in Space, American Society of Civil Engineers (ASCE)** 1996.

Nickel-Iron alloy (e.g., 1986DA; see Ostro et al, 1991)[9]. All of these substances would be useful and valuable feedstock in the construction of infrastructure and supply of fuel for development of an orbital economy. Any industrial development in orbit requiring more than a few hundred tonnes per year of structural material or propellant will direct attention to these sources as ores, in the mining engineering sense.

This will happen because raw materials retrieved from asteroidal sources will not attract the high "airfreight" costs imposed by launch from Earth. The energy requirement to return material from many of the possible target near-earth asteroids is much less than that required to launch from Earth. In addition, the freedom to deliver the velocity change non-impulsively means that low power propulsion systems are acceptable, thus permitting a propulsion system that uses solar power and derives its return-journey propellant from the target body, such as asteroidal volatiles.

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, Δv, needed to perform the transfer. Likely lowest Δv targets for initial resource development are specifically the low eccentricity, low inclination subset of the "Earth-Approaching" Apollo, Amor, or Aten asteroids; or any as-yet undiscovered Earth-Trojan asteroid. Shortlists of high accessibility NEAs are attached as Excel files; their delta-vs are calculated using the Helin-Shoemaker estimation formulae.

The mission velocity Δv needed to reach selected "near earth" low Δv target asteroids is not much greater than that needed to place a communications satellite in geosynchronous orbit (GEO). The Δv required to place material from these targets on an Earth-orbit-intercept trajectory may in selected cases be *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.

Note at the outset that we must make the caveat that the delta-v requirement for the return trip is much more important than the d-v outbound, because the return trip places the most severe demand on the propulsion system.

Target selection is important, because the lower the return propulsion requirement, the lower is the mass that has to be mined to produce propellant and therefore the lower may be the mining equipment mass, and the power supply mass, and the larger the proportion of recovered mass that can ultimately be sold for revenue.

It turns out that the major d-v requirement is for Earth-capture from heliocentric orbit into Highly Elliptical Earth Orbit, and then subsequently its reduction into LEO. Capture via powered or unpowered lunar flyby, followed by aerobraking (not aerocapture) will probably be part of the solution. This is discussed further below.

[9] Ostro S et al: *"Asteroid 1986DA: Radar Evidence for a Metallic Composition"*, **Science 252, June 7**, 1991.

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ISSN:1533-7405

4. IN-SITU PROPELLANT PRODUCTION

If the return transfer can be accomplished using ***part of the retrieved asteroidal 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. In other words,* in situ propellant production enables a high Mass Payback Ratio (mass multiplication). **Mass multiplication factors above 100 are the initial aim.**

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

5. OREBODIES IN SPACE – SOME MINING INDUSTRY CONCEPTS

Discussion of "Mines in Outer Space" generally produces raised eyebrows and other expressions of disbelief, however, mining has historically been successfully carried out in some extremely remote and inhospitable territory, and the basic principles of mining economics will still necessarily apply. The closest terrestrial analogs will <u>not</u> be large highly complex, highly competitive commodity producers, but will be small, remote mines extracting highly profitable very high value products. Examples that come to mind of high value, small volume producers are remote, high grade gold mines, diamond and other precious gem mines, radium mines in the 1920's (e.g. Shinkolobwe in the Belgian Congo and Port Radium in the Canadian NWT), and uranium mines in the period from 1944 to 1960.

Mining engineering philosophy states that mineral-bearing material is only 'ore' if you can successfully mine it, extract the valuable material, and sell the product to make a profit. A body of mineralization, no matter how high its grade, which cannot be accessed, or which is not amenable to successful mining, or which cannot be successfully treated to extract the contained valuable metal, **for sale at a profit**, is NOT ORE.

Similarly, *an asteroid mining proposal which cannot compete on economic terms will not fly!!*

Examples of technical problems which render mines infeasible, are: isolated location and difficulty of supply of required consumables; very difficult ground conditions which threaten the stability of underground openings; mineralization too fine for practical grinding technology to liberate; refractory ores which are not amenable to easy smelting. Note that having a high enough grade of deposit can swing the balance, because it allows the manager to spend more money per tonne of ore (on consumable transport costs, on ground control, or grinding technology and power, for example) to win the valuable product: "Grade Wins", as the mining engineers say. There are also political and economic factors which can determine whether a mineralized body is or is not "ore". For example, a mineralized body, of however high grade, located within a prohibited, sterilized, no-go area like (say) Yellowstone National Park, or downtown Tokyo, is not "ore", because it will never be made available to be mined. In an area with a firm rule of law, mining can only proceed on the basis of ownership of title to the property, or leasehold, or a commission from the government. If this is withheld, or is at risk, then the value of the property is again under question: it might not be 'ore'.

In an extraterritorial area, physical possession is all-important.

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:

(i) there needs to be a market for the products
(ii) need adequate spectral data indicating presence of the desired materials
(iii) check that orbital parameters give reasonable accessibility and mission duration
(iv) development of technically and economically feasible concepts for mining & processing
(v) development of technically and economically feasible retrieval concepts
(vi) require positive economic Net Present Value, using the chosen engineering concepts.

Point (ii) above is a problem, because spectroscopic data really only tells you about the composition of the top few microns of the surface. Deeper probing requires physical presence, i.e., a drill rig or kinetic penetrator.

Like terrestrial mining projects, each asteroidal resource project will have its own idiosyncrasies, reflected in the alternative product, process, and mission trajectory profiles to be considered.

The return of Platinum Group Metals to Earth has been discussed as a commercial possibility, by Jeff Kargel (JGR 99, Oct 1994, E10, p21129ff)[10], and more recently by Dennis Wingo (Space Front, September 2000)[11]. These metals are valued at roughly $10,000 to $20,000 per kilogram.

Water, nickel-iron, and semiconductor elements are all potential products for delivery and sale into low earth orbit, for use within in-space infrastructure. These products have a minimum value in LEO equal to the 'airfreight' cost of the alternative supply, which is launch from Earth. This is presently some $10,000 per kilogram. This cost will drop, for near-future reusable launchers, reducing initially to $1000 then to about $500 per kilogram. Thus, asteroidal raw material commodities will command a price in LEO which will generally track these values, over time.

In contrast with the situation that applies in terrestrial mining, where statistically one prospect out of several hundred investigated at desk-top-study stage may survive to become a paying mine, it is probable that a high proportion of NEAs could prove up as profitable resource bodies. This is because some 30% to 50% of them may be water-bearing, and water is the likely first valuable product to be searched for and returned from NEAs.

In contrast with terrestrial mining, where the product is either a relatively low value commodity like industrial metals e.g., copper, at (say) $2 per kilogram, present at a grade of (say) 1% by mass, or alternatively it is a high value metal present in extremely low grade, e.g., for open pit gold mines, 1 part per million (1 gram per tonne), in the case of asteroidal resources, space miners will be seeking to recover material of value in the first instance (say) $1000 per kilogram, which may be present in the 'matrix' material at a high grade of (say) 10% or more. A return payload of 1000 tonnes is thus worth (potentially) up to $1000 million dollars.

The high specific value and the high grade of deposits mean that the mass to be handled and recovered to pay back the project need only be small. The mass of mining equipment, processing equipment, and power supply required for generating an output of 1000 tonnes over a period of (say) six months may be quite small, depending on the assumed mass throughput ratio and on the assumed power to mass ratio of the power system.

[10] Kargel J: *"Metalliferous Asteroids as Potential Sources of Precious Metals"*, **Journal of Geophysical Research** 99 No E10 pp21129-21141, 25 Oct 1994.
[11] Wingo D et al: *"NEO Metals Resources and their value to the World Economy"*, **Space Front** (Journal of the Space Frontier Foundation) 8 No3 September 2000.

Mass of the mining plant can be very roughly assessed by comparison with the mass / mass-throughput ratios of materials-handling equipment in the mining industry. A classical very simple cable scraper ('slusher") can easily collect several hundred tonnes per day, for a unit mass, including its electric drive, of about half a tonne, giving a mass throughput ratio of (say) 700 kg per day per kg. A front-end loader can load a mass equal to its own mass in 3 minutes, for a mass throughput ratio of something like 500 per day.

Mass of simple processing plant (grinding and heating plant for example integrated hammermills-dryers of mass 200 kg handle 5 tonnes per hour) suggests mass throughput ratio of 500.

So the mass throughput ratio of the combined plant could thus conceivably be assessed to be 250 per day, suggesting the equipment mass for handling 10,000 tonnes of regolith in three months, to extract 1000 tonnes of product, could be something under half a tonne! Obviously this is a 'big ask', and it does not yet take into account the mass of ancillaries, nor importantly the mass of the power system, but it indicates what engineers might reasonably aim for.

The mass requirement for a solar thermal system might be very small: the L'Garde technology inflatable mirrors are very light. The IN-STEP inflatable mirror experiment orbited by the Shuttle in 1996 was a 14 metre diameter reflector with a mass of the order of 100 kg. If used as a solar collector its potential thermal power output would have been approximately 200 kW. Obviously, there are severe design requirements that have to be met for such a system to work. One downside is that a solar thermal system requires accurate steering, and another is that it is obviously quite fragile. These considerations impact on reliability.

Finally, there is the mass requirement for the product collection bag, and for the return propulsion system. These can be reviewed with various possibilities in mind, but a total system mass of a very few tonnes appears to be a near-term technical possibility. Miner mass of the order of a few tonnes clearly implies a non-manned, automatic miner.

We thus conceive that the mining and extraction plant may be very small and light, with correspondingly small capital expense ('CAPEX'). It may very well be regarded as 'throwaway'. Alternatively, the plant is certainly small enough to move it to a second, and a third, body, if mining is completed (or abandoned) at the first body, and provided there is adequate propellant for the move. This is a totally different and much more realistic scenario from those usually imagined, and originally conceptualized, of a large manned mission, costing billions of dollars to fund (e.g., O'Leary, Space Industrialization, CRC Press, 1982)[12].

The staged approach to terrestrial mineral exploration and development adopted by international mining companies is worth reviewing, and generally proceeds as follows:

<u>Strategic "Desktop" studies, to decide *what* to look for, and *where*:</u> In the terrestrial minerals exploration industry, exploration geologists bring to the task a mindset that recognizes that only a small proportion of identified potential prospects will survive feasibility culling to become a successful operating mine. The desktop study serves to develop the initial list of prospective areas, and the corporate exploration budget is geared to an understanding that maybe only one in a hundred of the prospects to be generated will ultimately advance to feasibility study level. A similar mindset will have to apply in asteroid mining ventures.

In the space resources scenario, the first valuable product will probably be water, supplied in LEO for Space Station orbit maintenance propulsion, and for RLV space-freighter de-orbit propellant. *The*

[12] O'Leary B: *"Space Industrialization",* **CRC Press**, 1982.

low-eccentricity and low-inclination Near Earth Asteroids are the targets of interest, for reason of the low delta-v's required for outbound and return trajectories.

Having decided what to look for, and where, then we perform more detailed open and proprietary data reviews: Government NEA search programs, astronomical research, university theses, etc., are reviewed. This enables more restricted target lists to be identified and prioritized. There is at present unfortunately a severe lack of spectral information available.

In the terrestrial mining situation, this is also the stage at which the mining corporation would look at the licencing / tenure regime, and at the potential licence conditions to be imposed by the government. In the space mining scenario, we are in a legal "terra nullius" - a land owned by no-one. This implies both serious threats and opportunities.

Progressively more specific (and more costly) screening, including possibly trial mining: In the space scenario, a precursor or prospector mission may be decided upon. Although it is generally assumed that prospector missions are essential, prior to the launch of a commercial asteroid miner, this is not *necessarily* so, as the following terrestrial examples show:

Case 1: A "wildcat" oil exploration well is always of a size to enable future full-scale production, should oil or gas be found. This is because the value of time saved in the event of a discovery, to bring the well into production, is large enough to justify the extra up-front cost.

Case 2: A mine exploration shaft or decline developed to gain access into a deep body of known but ill-defined mineralization is generally sized so as to accommodate initial mine production rates, and so save capital cost and time delay, should the deposit 'prove up'.

In the case of asteroid mining, if you miss 'this' mission opportunity, the next may not occur for the synodic period which may be as much as ten or more years later.

Project conceptual planning and prefeasibility studies: At this stage, the design team will begin to consider and review possible mining and processing methods. This conceptual project design work - the Prefeasibility Study - must consider the RESOURCE size, percent RECOVERY, and desired production RATE, to develop a

Mining Plan, and a
Metallurgical Process Flowsheet, which
minimizes Capital Expenditure,
minimizes Payback Time, and hence

Maximizes the Expected Net Present Value.

"The Technical and Economic Feasibility of Mining the Near Earth Asteroids", (Sonter 1997)[13] *showed how to carry out a generic scoping and prefeasibility study for hypothetical asteroid mining projects for water recovery including how to calculate net present value for these ventures.*

Generally then in the terrestrial case a Final Feasibility Study is performed in parallel with an obligatory Environmental Impact Statement. Sometimes the EIS uncovers a previously unconsidered constraint, which may demand a major change in plans, or may even scuttle the project, depending on the cost implications. (The EIS process is important, because an overlooked constraint which causes

[13] Sonter MJ: *"The Technical and Economic Feasibility of Mining the Near-Earth Asteroids"*, MSc (Hons) thesis, **University of Wollongong**, 1997.

catastrophic failure can end up costing the proponent millions or even billions in compensation and rehabilitation.)

6. ECONOMIC FEASIBILITY AS THE 'SINE QUA NON'

A project will not attract investment unless it can be reasonably expected to pay for itself. The business plan needs to address the following questions:

- What are your market assumptions?
- What is your desired production rate?
- What, therefore, is your expected revenue?
- What is the expected operating cost?
- What is your target Capital Cost?
- What, finally, is the project's calculated Net Present Value?

The capital cost of any envisaged asteroid mining project MUST be capable of being paid back (several times over) out of profits in a period of (say) 3 years at most. This, taken in conjunction with orbital mechanics constraints, implies short-term mining missions, limited to 'out and back' sorties, with probably only 3 to 6 months of actual mining on the body.

An asteroid mining project must promise a large positive NPV or it will not fly!!

Implications of the "Economic Imperative":

"Minimize CAPEX":	unmanned; single or at most double launch; simplest possible systems.
"Minimize Payback Time":	minimum duration mission cycle; implies low eccentricity NEA.
"Maximize NPV":	lowest delta-v for return, including capture; highest-yield target; simplest possible extraction system.

7. CORPORATE STRATEGY DEMANDS FOR RESOURCE COMPANIES

It is useful also to review a hypothetical asteroid mining project in the light of the strategic, as well as the economic requirements of mining corporations. A major strategic concern of resource corporations is "How to obtain sustainable strong growth?" - preferably in an expanding, not a mature, market. There is thus a need to seek to identify and develop high growth, high profit, products. There is also a need to create a "sustainable competitive advantage", which will generally derive from (i) proprietary knowledge; and / or (ii) a superlative orebody of high grade, long life and low cost.

A *'virtuous circle'* is thus developed:

PROPRIETARY KNOWLEDGE delivers **FIRST IN MARKET (AND / OR SUPERLATIVE OREBODIES)** which delivers **REDUCED RISK & COST** which delivers **OVERWHELMING ONGOING (SUSTAINABLE) TECHNICAL AND ECONOMIC COMPETITIVE ADVANTAGE.**

The well-timed opening up of asteroid resources will provide this *'first movers'* advantage.

Other areas of strategic concern to resource companies are restrictions on land access, and constraints on waste disposal:

The CEO of Nautilus Minerals Corp, Julian Malnic, in comments supporting his company's plans for deep seabed mining of massive sulphide deposits, says " the two most intractable threats (to the traditional terrestrial mining industry) are land access problems … and increasing constraints on tailings and mine waste disposal." (Bulletin of the Australasian Institute of Mining and Metallurgy, October, 2000)[14] Asteroid mining will be essentially free of these threats. Malnic also claims a number of competitive advantages for Seafloor Massive Sulphide deposits, vis-à-vis terrestrial mining projects, which similarly apply to asteroidal ventures, as below:

1. High proportion of targets are likely to succeed as 'orebodies'
2. High grade implies easy extractive metallurgy
3. No landowner or environmental access constraints
4. Short lead-time to production – initial mission may return product – trial mining is easy
5. No large CAPEX (mine, plant, town, port, infrastructure) costs
6. Plant is so small and cheap that it is essentially throwaway
7. Feasibility hurdles lowered due to ability to move to a new target if first target is no good
8. Plant is naturally relocatable at end of 'mine life'
9. Plant may be leased (essentially eliminates capex)
10. Waste disposal is not a concern

8. REVIEW OF ASTEROID RESOURCES

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

Table 2 Matrix of spectral type, inferred mineralogy, and potential products.

Type	Inferred Mineralogy	Product
C, D, P	clay, organics, ice at depth?	volatiles: H_2O, CO_2, CH_4
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), semiconductors

Dormant or extinct cometary bodies (there are several likely candidates), may contain remnant primordial ices at depth, making them possible sources of volatiles for future space industry.

9. MISSION PLANS AND TRAJECTORIES

Considerations of celestial mechanics show that *(i)* simple estimates of "global minimum" delta-v are available; *(ii)* the launch windows for these "global minimum" opportunities are infrequent, but somewhat higher energy local minima occur more frequently, for most NEAs; *(iii)* long synodic periods militate against multiple-return mining missions; *(iv)* Earth-return hyperbolic velocity should be kept low; *(v)* high-

[14] Malnic J: *"Factors in the Financing of Seafloor Massive Sulphides Exploration",* **Australasian Institute of Mining and Metallurgy Bulletin**, Oct. 2000.

eccentricity targets imply Hohmann transfers, and short mining season at aphelion; *(vi)* low-eccentricity targets allow continuous thrusting propulsion, and extended mining season.

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 several 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;
- if 'short-term' mining season, it may be aphelion-centred or perihelion-centred.

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 limited to a short period during aphelion; return Δv 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-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 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 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 hence reduce Project NPV. To minimise return departure delta-v, the object's orbit should be "Earth-grazing", i.e., $q \cong 1.0$ AU.

"Aten-Type": 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 this gives inadequate mining season duration.

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

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 longer return trip duration, 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 v_{hyp} (hyperbolic 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).

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, ($\Delta v_{inclin} \cong 0.5 \times i$ km/sec.), so timing of mission phases with respect to Ascending / Descending Nodes is important for these cases.

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:

- use *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.
- use an Earth-fabricated, LEO-fabricated, or asteroid-fabricated *aerobrake*.
- use *lunar flyby* to remove hyperbolic Δv. This will naturally insert the returning craft into HEEO (Highly Elliptical Earth Orbit). 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/sec has been quoted for a single lunar flyby. This applies 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.

Arguments against Multiple Trip Scenarios: Repeated returns to the same target asteroid have been dismissed from consideration because:

- the high required Internal Rate of Return means that sales receipts of subsequent missions are heavily discounted;
- 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;
- the operator will want to recover the remote miner and refurbish and upgrade it;
- it is assumed that lessons learned after the first mission will dictate modifications to both the equipment and the mission planning.
- the most accessible bodies have long synodic periods.

Conclusions regarding Mission Trajectory Types:

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

10. CONCEPTS FOR MINING, PROCESSING, POWER, AND PROPULSION

The concepts discussed here focus on the design for the simplest, minimum mass, minimum 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 or mining.

Engineering Choices can be identified as follows:

product : water; Ni-Fe metal; gases; silicates; PGMs; semiconductors.

mining method : surface mechanical; volatile production via greenhouse bubble; underground mechanical; in-situ volatilization; other down-borehole approaches.

process : volatiles - insitu volatilization and extraction; excavate, heat, dehydrate, and condense. Metals - 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, microwave thermal, regolith rocket.

Product and process are linked, as shown below.

Possible Products and Sources

Type	**Product and Process**	
	Volatiles	Structural materials
"cryptocometary"	H_2O, CO_2 Thermal devolatilization	----------
carbonaceous	H_2O, CO_2 thermal dehydration	NiFe metal density or magnetic separation
ordinary chondrite	----------	NiFe, PGMs, silicates density or magnetic separation
metallic	----------	NiFe, Platinum Group Metals carbonyl process

For volatiles production, the process choice may be recovery by surface soil collection or subsurface matrix excavation, followed by extraction of volatiles by heating, or by drilling through surface crust then in-situ fluidization of subsurface volatiles (Kuck, In Situ Recovery of Water from Dormant Comet

Cores, 1992)[15]. For metal production, surface regolith collection then separation using density, electrostatic, or magnetic methods would be used. Extraction of PGMs probably requires use of the carbonyl process.

Mining methods:

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 escape velocity for small asteroids or dormant comets 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 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 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 - requires you assume the material is mechanically competent
- fire in harpoons or penetrators which resist extraction
- screw in large area augers or screw-plates - requires assumption that there is a regolith and it is loose enough and compressible enough for 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)

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 shovelled. 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 (eg impact of a pick, pressurization of a drill hole by an explosion, or static loading by the teeth of a roadheader or cutting discs of a tunnelborer). Classical percussion drills use the inertia (of the jumbo 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.

[15] (Kuck, In Situ Recovery of Water from Dormant Comet Cores, 1992)

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, eg. using the carbonyl vapour-metallurgical process, as proposed by Lewis and Nozette (1983)[16] and Lewis, Jones, and Farrand (1988)[17].

Surface mining

Gertsch (1984)[18] proposed the classical three-drum slusher/scraper for lunar regolith mining operations, because of its simplicity and low mass. This however is probably inapplicable to asteroids, where the overriding considerations appear to be (i) very low strength regolith; (ii) essentially zero gravity; (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 doesn't "float away". Thus, mining on low gravity bodies will require an approach which encloses the regolith being collected, eg 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.

Underground extraction

There may be good reasons to use underground mining techniques when mining on asteroids:
(i) easier to generate reaction forces for cutting, drilling, or digging (i.e., more "normal" technology)
(ii) the surface layer may be depleted in the desired material (e.g., volatiles at depth under a lag deposit in a dormant comet)
(iii) it may be easier to contain the cut or released material.
(iv) 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 which is suspected to be weak and friable. (Even in milli-g, failures of ground will be inconvenient).

In-situ extraction

A particular case of underground extraction is by fluid extraction through drillholes (Kuck 1995)[19]. 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 practised in in-situ leach mining of uranium orebodies, 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

[16] Lewis and Nozette (1983)
[17] Lewis, Jones, and Farrand (1988)
[18] Gertsch R: *"Asteroid Mining"*, in **Space Resources, NASA Publ SP-509**, ed McKay and Duke, 1992 (Proceedings of NASA-ASEE Summer Study Workshop at California Space Institute, 1984).
[19] Kuck DL: *"The Exploitation of Space Oases"*, in **Princeton Conference on Space Manufacturing,** SSI, 1995.

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 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. A greater threat (and probable 'show-stopper') is that pressurization of the 'mining void' within the hypothesised 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.

Regolith Devolatilization Process: The soil devolatilization process requires a more complex materials handling plant, since it demands an actual mining plant, and 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 - 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 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 mass of the return propulsion system.

Propulsion and power choices are also 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

		Propulsion		
		steam rocket	Arcjet/MET	mass driver
Power	solar thermal	Yes	No	No
	Solar PV	No	Yes	Yes
	nuclear	Yes (no)	Yes (no)	Yes (no)

(the nuclear options are bracketed 'no' because they are politically unavailable)
(MET: Microwave Electrothermal Thruster)

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.

11. 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. 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 annum, to compete successfully for the required funding.

It has been noted in the literature (Cutler & Hughes, 1985[20]; Lewis Ramohalli & Triffet, 1990[21]; Ramohalli, Kirsch, & Priess, 1994[22]; Oxnevad, 1991)[23] 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:

"Through extensive sensitivity analysis, it was... shown that launch cost (was) <u>not</u> a critical parameter." - Oxnevad, "An Investment Analysis Model for Space Mining Ventures" (1991).

Simple 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 state that "high MPBR is not particularly important. <u>Low initial capital ***is*** important</u>.... Optimising selected physical parameters such as delta-v or Isp does <u>not</u> in general lead to the most economical system." (present author's emphasis)

"A *general economic methodology to evaluate schemes for extraterrestrial 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."

To summarise, there is a need for a robust general approach to 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:

- alternative target asteroids / comets / moons
- alternative mission types
- alternative propulsion methods and propellants
- alternative power sources
- alternative target materials to be reclaimed (volatiles, metals, PGMs, semiconductors.)
- alternative materials reclaim and processing methods

[20] Cutler and Hughes: "Transportation Economics of Extraterrestrial Resource Utilization", AIAA/SSI 1985.
[21] Lewis Ramohalli and Triffet: *"Extraterrestrial Resource Utilization for Economy in Space Missions"*, International Astronautical Federation Conference 1990.
[22] Ramohalli, Kirsch, & Priess, 1994
[23] Oxnevad K: "An Investment Analysis Model for Space Mining Ventures", International Astronautical Federation Conference, 1991.

- guidance, navigation, and control, both outbound and return
- autonomous control of mining and processing activities
- alternatives for sizing of minimum feasible project.

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

NPV Discussion and formula derivation

The proper "figure of merit" used to assess financial feasibility of proposed projects is the Net Present Value, or more correctly, the *Expectation* NPV taking into account the probabilities Pi, i = 1,….n, to enumerate all the probabilities of all the success, partial success, and failure scenarios.

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. 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 Δv is not critical, except within the constraints of the launcher capability, return Δv 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 resource 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.

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

$NPV = R \times (1+i)^{-n} - \text{Capital}$, where i is the market interest rate paid on investments.

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, using the Rocket Equation and Kepler's Law determining the period of an orbit:

$$\mathbf{NPV = \$/kg_{orbit} \times M_{mpe} \times f \times t \times \%recov \times e^{-\Delta v/ve} \times (1+i)^{-(a^{3/2})} - ((M_{mpe} + M_{ps} + M_{i\&c}) \times \$/kg_{manuf}) + (annual\ budget \times n))}$$

where **$/kg** $_{\mathbf{orbit}}$ is the per kilogram Earth-to-orbit launch cost
M $_{\mathbf{mpe}}$ is mass of mining and processing equipment
f is the specific mass throughput ratio for the miner
t is the mining period
%recov is the percentage recovery of the valuable material from the ore
Δv is the velocity increment needed for the return trajectory
$\mathbf{v_e}$ is the propulsion system exhaust velocity
i is the market interest rate

a is semi-major axis of transfer orbit
M $_{ps}$ is mass of power supply
M $_{i\&c}$ is mass of instrumentation and control
$/kg $_{manuf}$ is the specific cost of manufacture of the miner etc.

The Δv values must be calculated from celestial mechanics for the particular trajectories chosen.

Process for determining NPV

The process for determining feasibility is thus as follows:

1. set required payload to be returned.
2. find Δv (return) from target body using Hohmann transfer calc or otherwise.
3. adjust for Δv reqd for inclination change (i in degrees):
4. from propulsion system I_{sp}, calculate propellant requirement;
5. determine mining stay time, and assume some recovery (say 10% of bulk feed); hence determine power required by the miner to process the required 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.

12. CONCLUDING SUMMARY

Some (low eccentricity) 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.

There is a future market (presently hypothetical) is for asteroid-derived material delivered into low-earth-orbit for sale to operators and constructors of LEO infrastructure such as space stations, exotic materials factories, orbital hotels and satellite solar power stations.

These raw materials will be competing against earth-launched materials, and earth-launch cost at this future time will be in the order of $500 per kilogram (because if the launch cost is much higher, these large-scale commercial infrastructures will not have commenced).

The obvious 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). A by-product may be Platinum Group Metals (PGMs), for export to Earth.

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.

The NEA discovery rate is now quite high, above 200 per year, with a substantial number being 300 metres diameter or more.

There is a subset of about 100 Near-Earth-Asteroids that are easier to get to (lower delta-v) than soft-landing on the Moon. And delta-v for injection into a trajectory to return to Earth from some of these can be very low indeed – some are under 1km/sec. This implies a low propellant use (for delta-v's less than 2.4km/sec, less than 50% of water is used, assuming 2400K exhaust temperature).

It is believed that ~30% of all NEAs are water-bearing objects. So "orebodies" should be easy to find, unlike the situation on earth.

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.

Target accessibility depends on velocity change Δv 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.

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'.

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")

Return missions to a particular body do <u>not</u> appear to be strongly advantageous, c.f. a new target.

Mining and processing methods for volatiles recovery and for metals recovery can be readily conceptualized and are being developed. 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; thermal power requirements 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.

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

Project economics is driven by mission velocity requirements, by the propulsion system characteristics (particularly Isp), 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 Low Earth Orbit, 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, ie time duration from launch to product delivery in LEO (this is related to the period of the Transfer Orbit from Earth to Target and return, and to duration of 'mining season'), and the value of the product once delivered into LEO, and market interest rate.

Expectation / probability of success relates to the technical choices and their maturity. The technical choices also impact on one another.

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 terms of the Rocket Equation and astronautical and celestial mechanics variables, enables a systematic 'roadmap' approach to project feasibility determination.

In conclusion, this work provides an outline for a rigorous approach to performing Feasibility Studies on asteroid and comet mining ventures. The concept of NPV can and indeed must be used as a 'design-driver' and reality check in project concept selection and development. NPV provides a way of sieving the concepts which will not survive economically.

Acknowledgement:
This work has been supported in part by a grant from the Foundation for the International Non-governmental Development of Space (FINDS).

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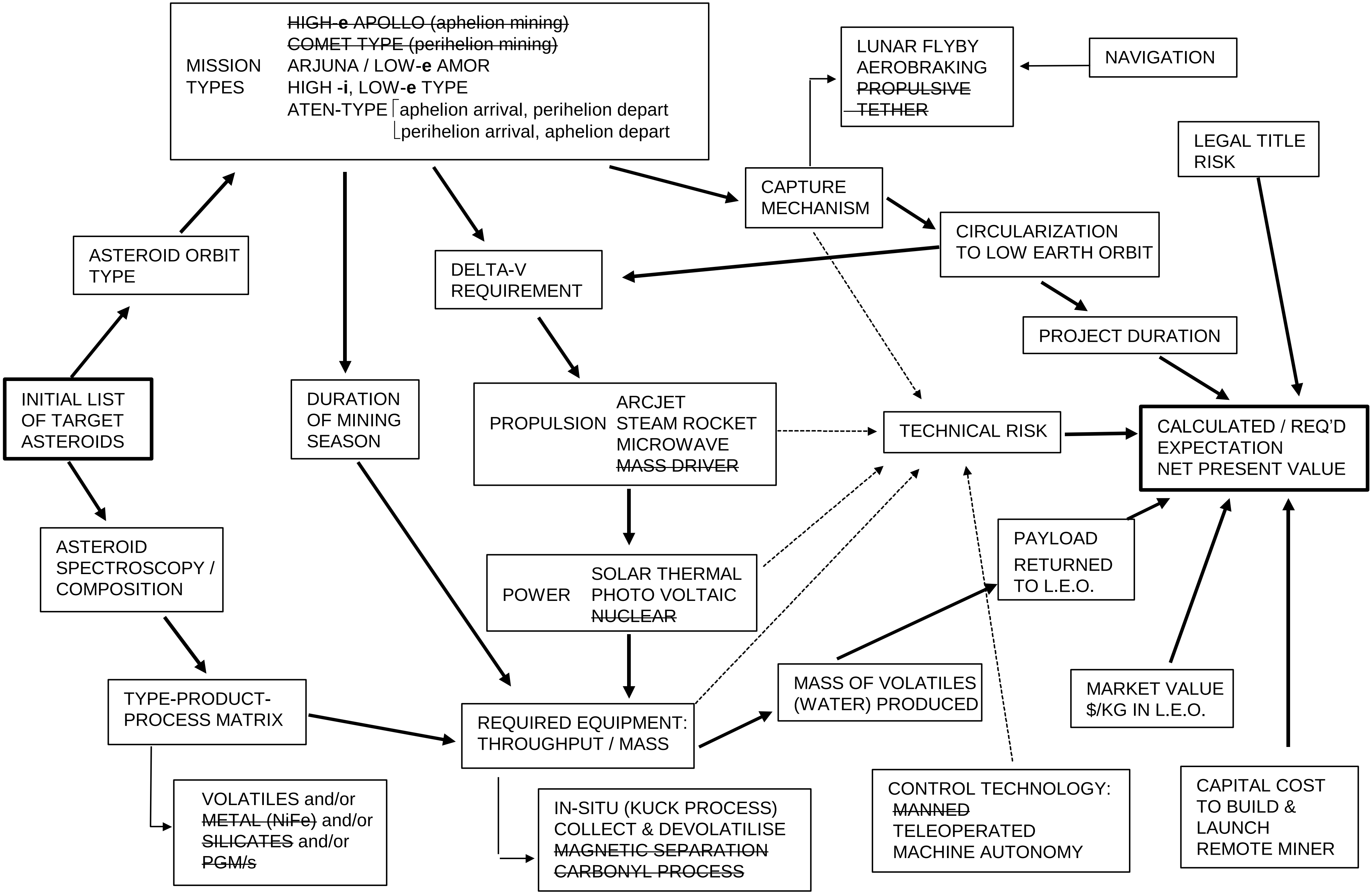
Attachments:

Excel files: ShortlistAtens; ShortlistApollos; ShortlistAmors.

These short lists of potential low delta-v targets are extracted from lists of all known Apollo, Amor and Aten asteroids published by the Minor Planet Centre, as of August 2000. Delta-v calculations are 'global minimum' estimates produced using the formulae given in the paper by Helin and Shoemaker cited in the References.


MISSION TYPES
~~HIGH-**e** APOLLO (aphelion mining)~~
~~COMET TYPE (perihelion mining)~~
ARJUNA / LOW-**e** AMOR
HIGH -**i**, LOW-**e** TYPE
ATEN-TYPE aphelion arrival, perihelion depart
perihelion arrival, aphelion depart
LUNAR FLYBY
AEROBRAKING
~~PROPULSIVE~~
~~TETHER~~
NAVIGATION
LEGAL TITLE RISK
CAPTURE MECHANISM
CIRCULARIZATION TO LOW EARTH ORBIT
ASTEROID ORBIT TYPE
DELTA-V REQUIREMENT
PROJECT DURATION
INITIAL LIST OF TARGET ASTEROIDS
DURATION OF MINING SEASON
PROPULSION
ARCJET
STEAM ROCKET
MICROWAVE
~~MASS DRIVER~~
TECHNICAL RISK
CALCULATED / REQ'D EXPECTATION NET PRESENT VALUE
ASTEROID SPECTROSCOPY / COMPOSITION
POWER
SOLAR THERMAL
PHOTO VOLTAIC
~~NUCLEAR~~
PAYLOAD RETURNED TO L.E.O.
TYPE-PRODUCT-PROCESS MATRIX
MASS OF VOLATILES (WATER) PRODUCED
MARKET VALUE $/KG IN L.E.O.
REQUIRED EQUIPMENT: THROUGHPUT / MASS
VOLATILES and/or
~~METAL (NiFe)~~ and/or
~~SILICATES~~ and/or
~~PGM/s~~
IN-SITU (KUCK PROCESS)
COLLECT & DEVOLATILISE
~~MAGNETIC SEPARATION~~
~~CARBONYL PROCESS~~
CONTROL TECHNOLOGY:
~~MANNED~~
TELEOPERATED
MACHINE AUTONOMY
CAPITAL COST TO BUILD & LAUNCH REMOTE MINER